Thermal Design in Electronics Packaging

Presented by

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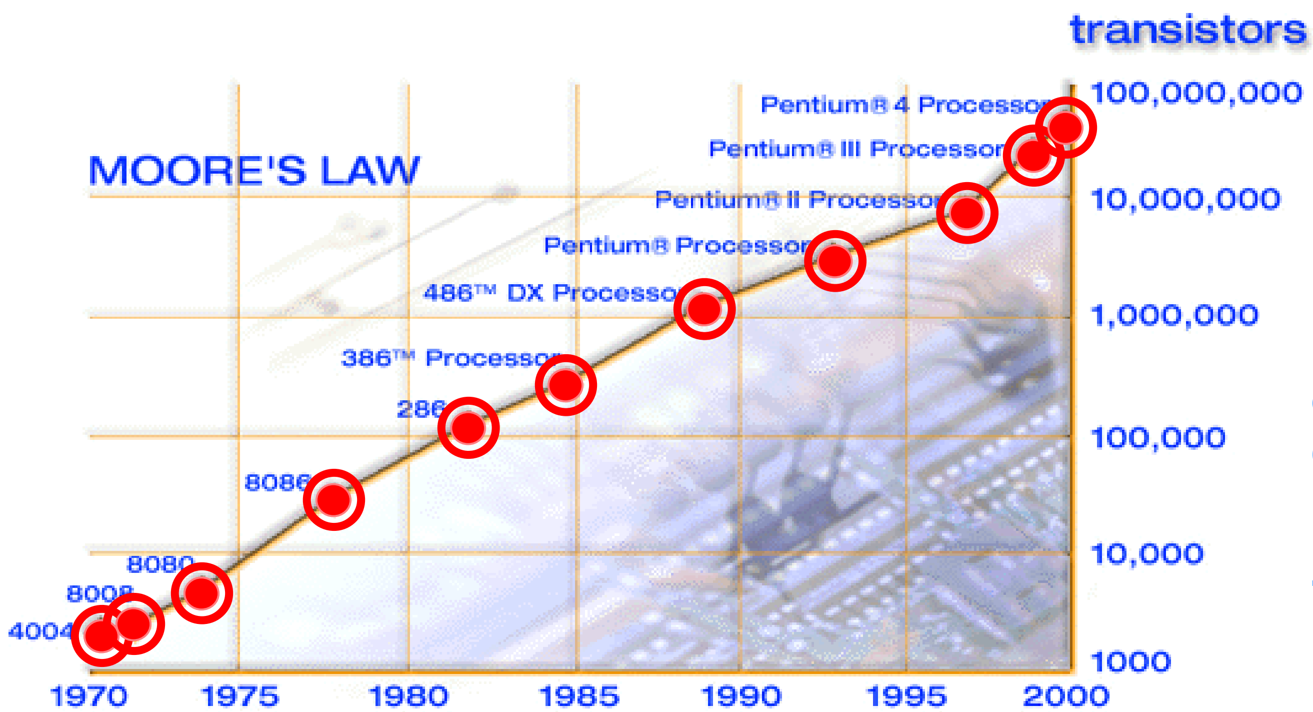
Agenda

- Thermal Trends and Challenges in Electronics Packaging
- Effects of Temperature on Reliability of Electronics Equipment
- Nature of Thermal Design in Electronics
- Thermal Design Best Practices
  - Understanding Fans and System Architecture
- Some Case Studies

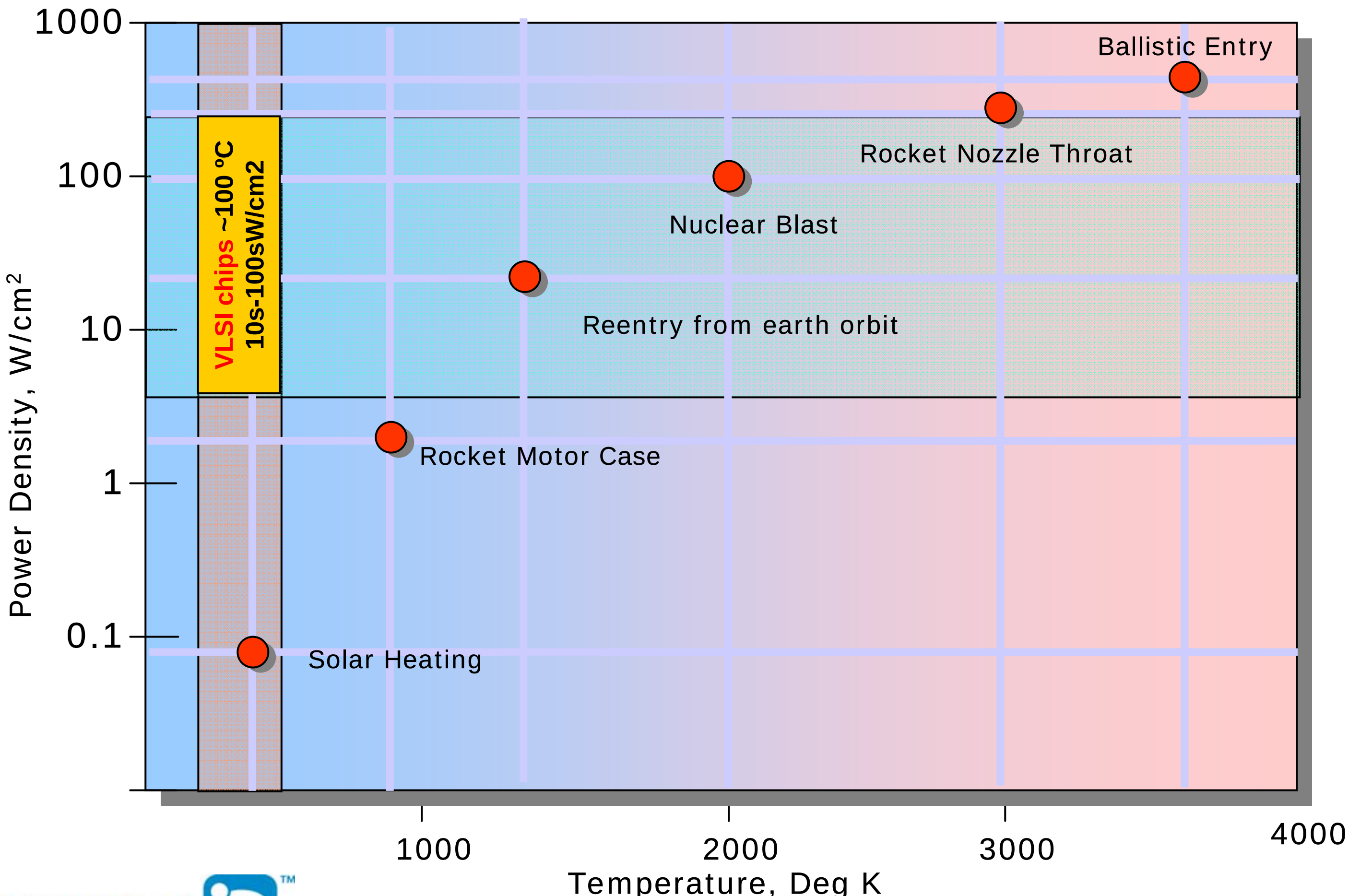
Thermal Challenge in Electronics Industry



"Number of devices that can be packed in a chip doubles every 18 months"

- Dr. Gordon Moore

Thermal Density: A Comparison



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New Challenges. Old Constraints.

- Watts per unit area in chip and equipment up several folds
- New low power semiconductor technologies out-paced by faster device density growth
- Heat removal technologies slow to catch up
- Operating temp ranges of devices have not changed much in thirty years
- “Thermal” is the key design constraint

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Thermal Design is Critical to Product Reliability

- The prime cause of failure of electronic equipment is temperature related
- Must keep temperatures under control to ensure reliable operation for better reliability
- Device power dissipations are increasing rapidly with speed and device density
- Thermal design is a major limiting factor in performance.
- Thermal solutions are nearing applicable physics
- Great opportunity for Thermal Experts!

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Why is Temperature Detrimental to Reliable Operation of Electronics?

- Temperature accelerates the following failure mechanisms:

  (1) Chemical Reactions
  (2) Diffusion Effects
  (3) Dielectric Breakdown
  (4) Ion Movement
  (5) Electromigration
  (6) Material Creep
  (7) Thermal Cycling (Fatigue in solder joints)
  (8) Board Warpage
  (9) Performance Drift

Electronics Device Reliability is Dependent on Temperature

Product reliability is defined as:

$$R(t) = 1 - F(t)$$

where:

R(t) = Reliability,

F(t) = Probability of failure

t = Time

In practice, we determine a failure rate λ (t) experimentally, and can relate it to R(t) as:

$$R(t) = e^{\left[-\int_0^t \lambda(x)dx \right]} \quad (1)$$

For electronic devices, λ (t) is a constant. *Therefore*:

$$R(t) = \exp(-\lambda(t)) \quad (2)$$

Electronics Device Reliability is Dependent on Temperature

- The temperature effect on failure mechanisms such as chemical reactions is given by:

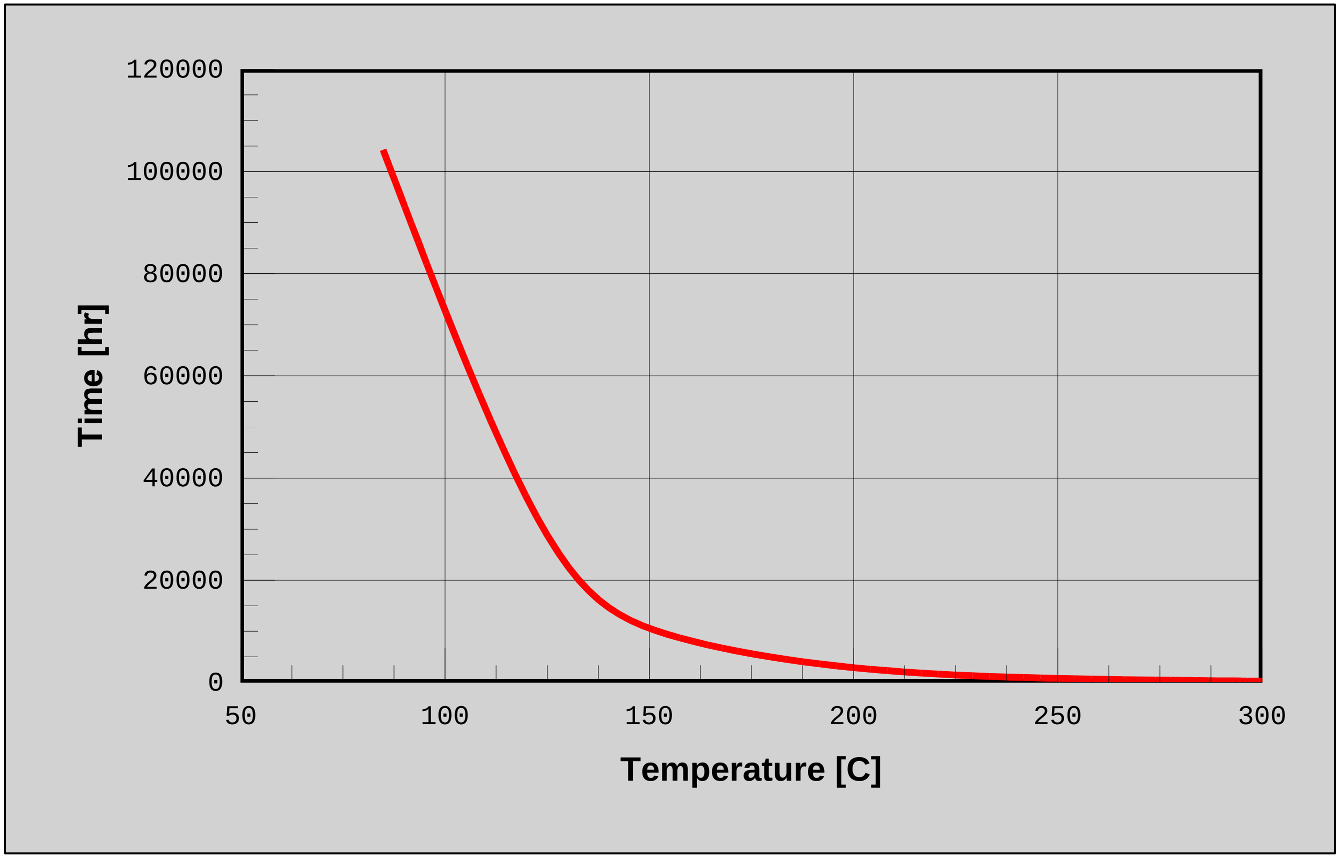
$$R = R_0 e^{\left(\frac{E_a}{kT}\right)} \quad (3)$$

- Time to failure is related to temperature as:

$$t_f = t_0 e^{\left(\frac{E_a}{kT}\right)} \quad (4)$$

- E_a is the activation energy; typically 0.5 TO 1.0 eV for Si devices and 1.5-1.6 eV for GaAs
- k is Boltzmann constant = 1.3802E-23 J/ºK, and T is the temperature in ºK.

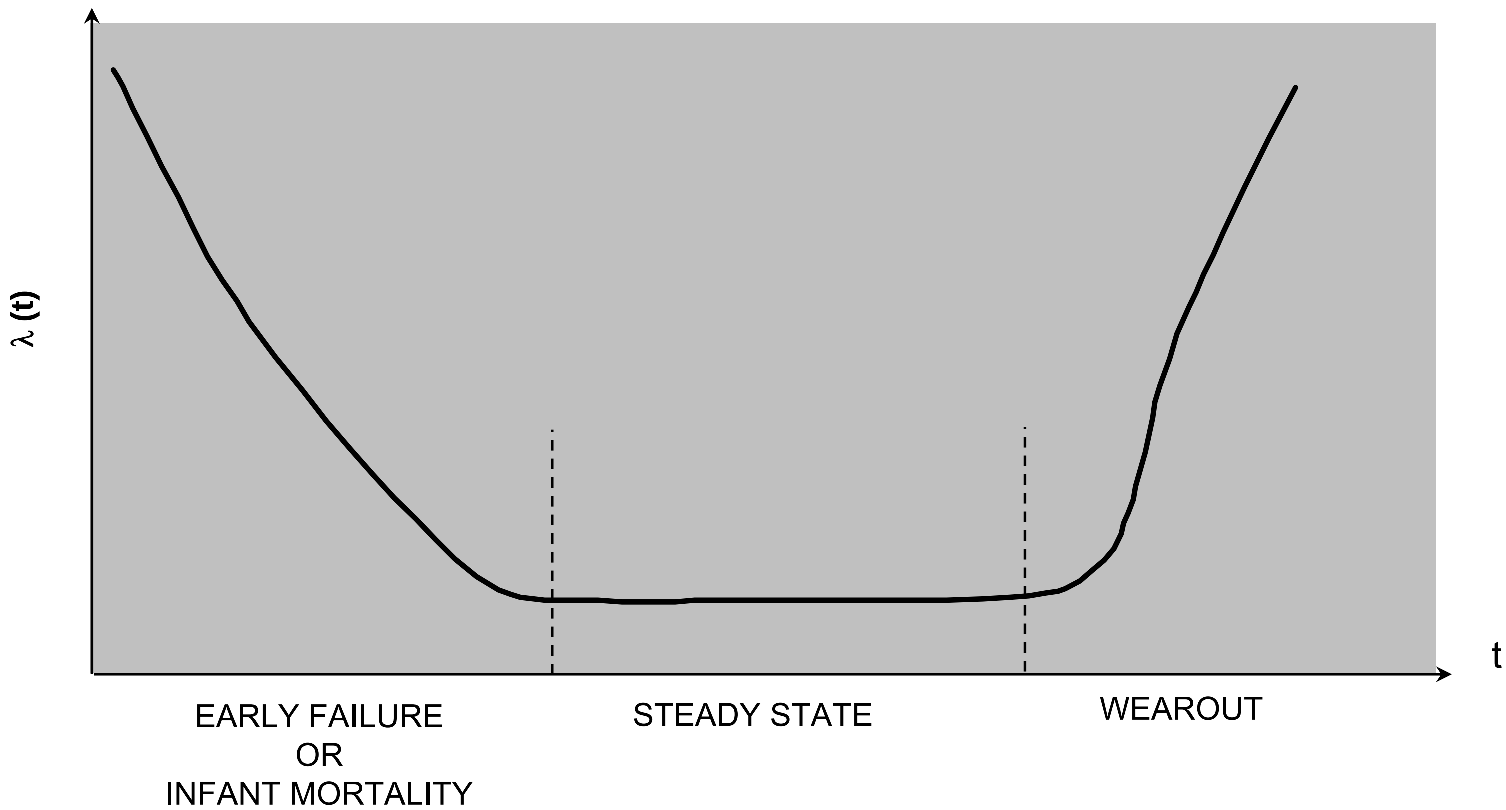
Life Equivalent to 40 Years in Hours



Relative to 60 °C Ambient. Ea=1eV

The Bathtub Curve

Failure Rates for Typical ICs with Time



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- ❑ Thermal Trends and Challenges in Electronics Packaging
- ❑ Effects of Temperature on Reliability of Electronics Equipment
- ❑ The Nature of Thermal Design in Electronics
- ❑ Thermal Design Best Practices
  - ❖ Understanding Fans and System Architecture
- ❑ Some Case Studies

Nature of Thermal Design in Electronics

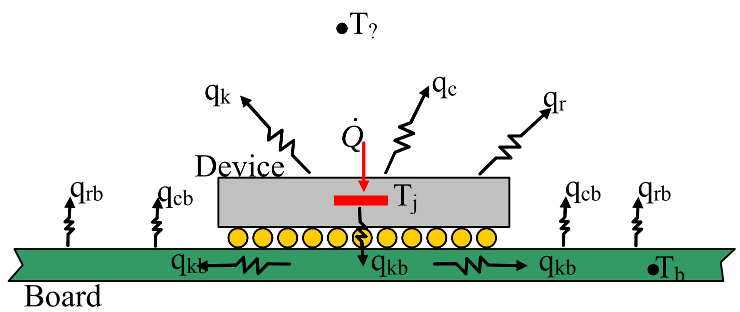
- Thermal Design of Electronic Equipment is a Multi-Faceted Heat Transfer Subject
- Invokes all areas of Heat Transfer, such as:
  - Conduction, Convection and Radiation,
  - Fluid Flow and Pressure Drop,
  - Extended Surfaces (Heat Sinks, Fins),
  - Experimental Techniques,
  - Empirical Data Analysis,
  - Numerical or Computational Methods,
  - Heat Exchanger Design.

Nature of Thermal Design in Electronics

- Heat Transfer is an Empirical Science (at Best)
- Accurate Thermal Prediction within Equipment is a Difficult Task!!! *Why??*
  - Complex Geometry, Bends, Obstructions, etc...
  - Non-Uniform Component Sizes and Layout,
  - Non-Uniform Board Spacing and Heat Dissipations,
  - Non-Uniform Flow and Velocity Distributions Within Equipment
- Accurate thermal modeling is critical
- Select the right modeling tool for the application
- There is no substitute for experience
- Conduct validation tests whenever possible

The Fundamental Problem

- Keep junction temperatures of all devices at safe values under all operating conditions
- Keep board temperature below 105ºC



T_{max} ? T_j >

- Important Deployment considerations:
  - Compliance and Safety
  - Ambient temperatures
  - Altitudes
  - Air conditioning failure
  - Solar heat loads
  - Weight and mobility
  - Cost

Component or Package Thermal Characterization

- For reliability and performance purposes, equipment designers are ultimately interested in device junction temperatures

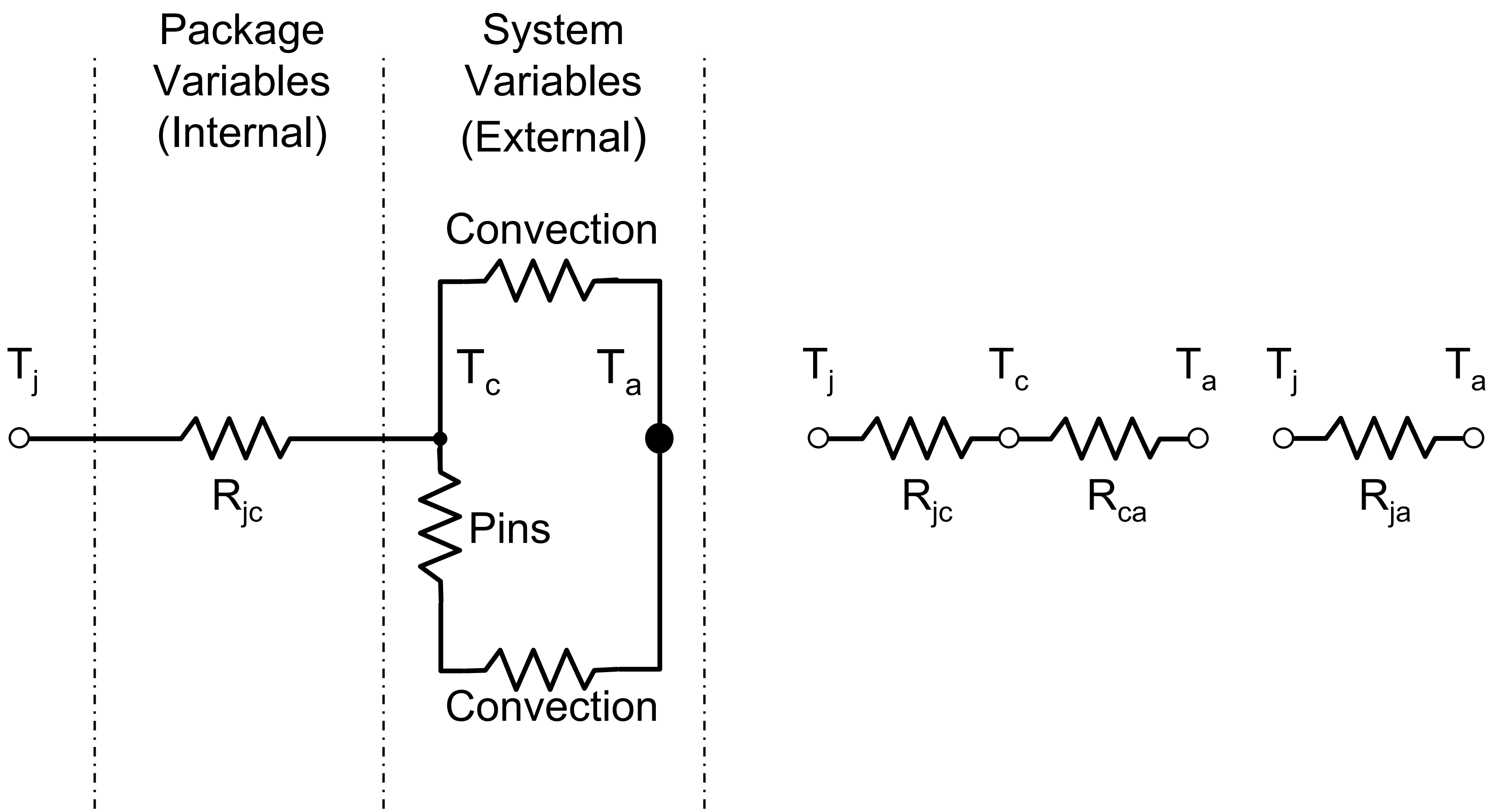
- Heat is dissipated in the device junction, which is conducted through the body of the package and the leads to the board and local ambient

- The ambient is the ultimate heat sink. Heat flows from junction to ambient through two parallel paths
  - junction to package case to ambient (q_1),
  - from junction to board (through leads) to ambient (q_2)

- It is often difficult to separate the amount of heat flowing in these two parallel paths. To overcome this difficulty, we define a net thermal resistance from junction to ambient as:

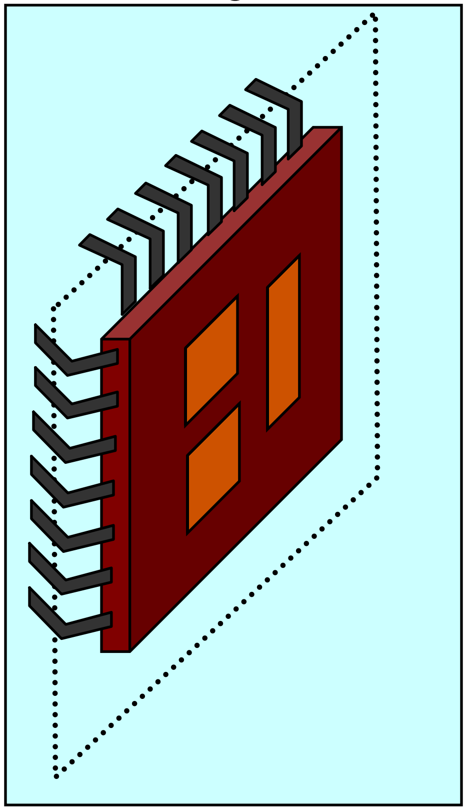
$$R_{ja} = \frac{T_j - T_a}{P} \quad (5)$$

Overall Model for Heat Flow from Junction to Ambient



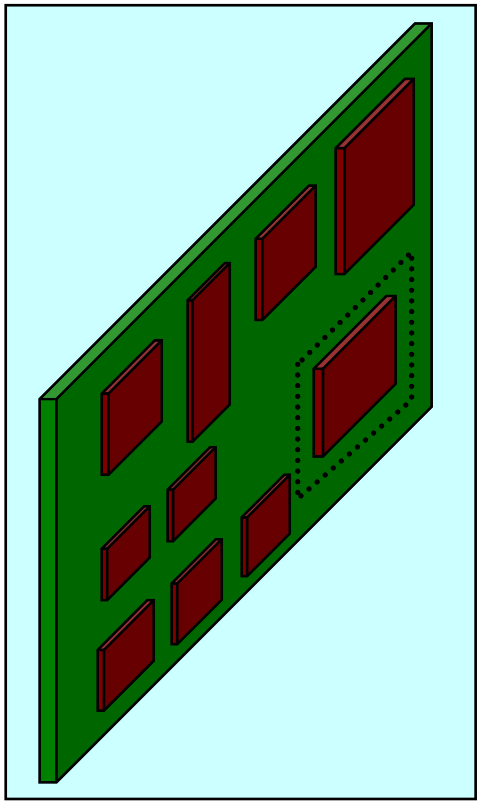
Thermal Design Hierarchy in Electronics

Package Level



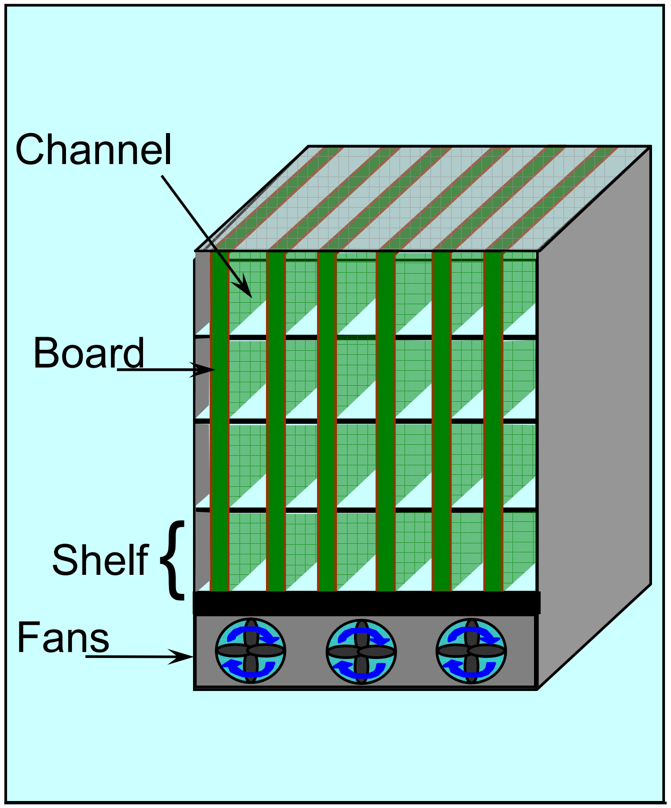
Thermal Characterization of Individual Devices

Circuit Board Level



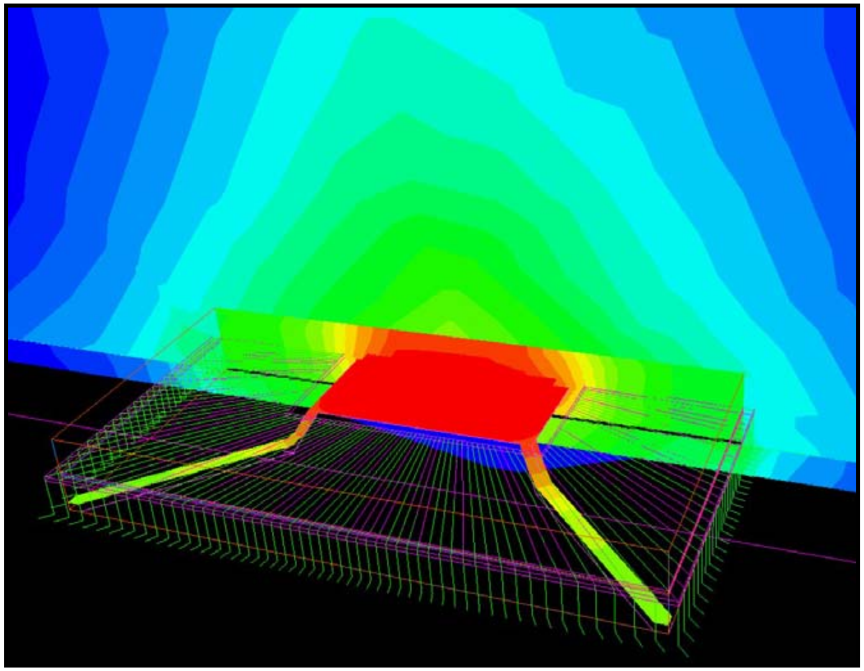
Device performance as mounted, under an assumed environment

Frame or System Level



Device performance as deployed

Device-Level Thermal Design

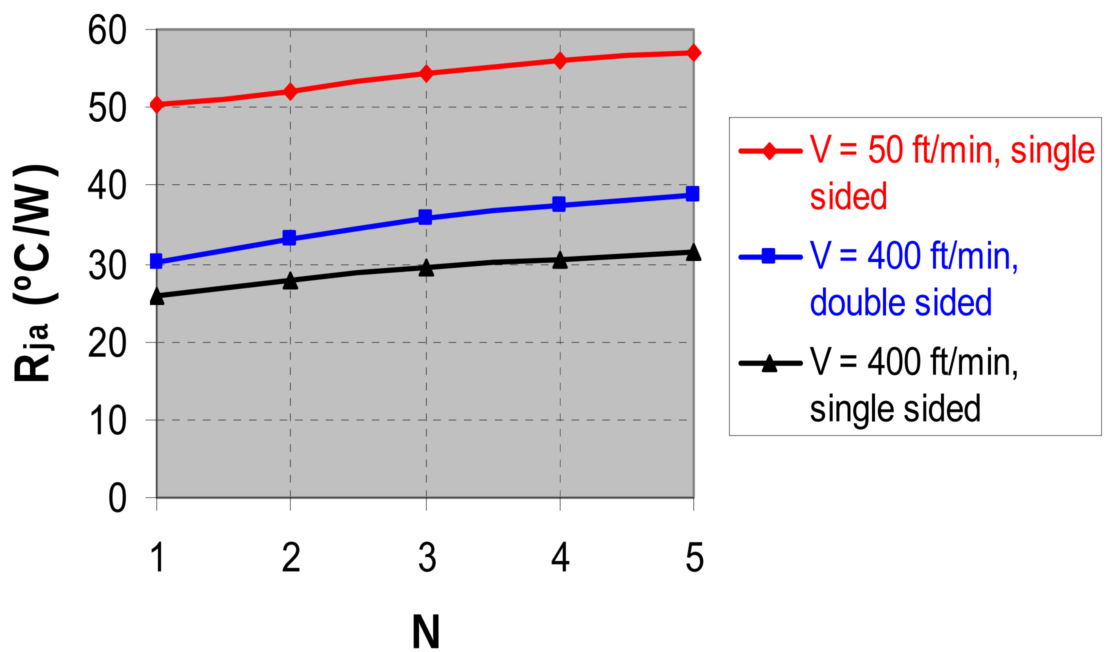


Considerations:

- Packaging Design – integrated heat spreaders, multi-core technology, etc
- Thermal vias – use board ground plane as heatsink
- Heat sink
- Thermal pads
- Min airflow required
- Orientation

Device-Level Thermal Design

Thermal Resistance of 68 I/O PLCC Package:



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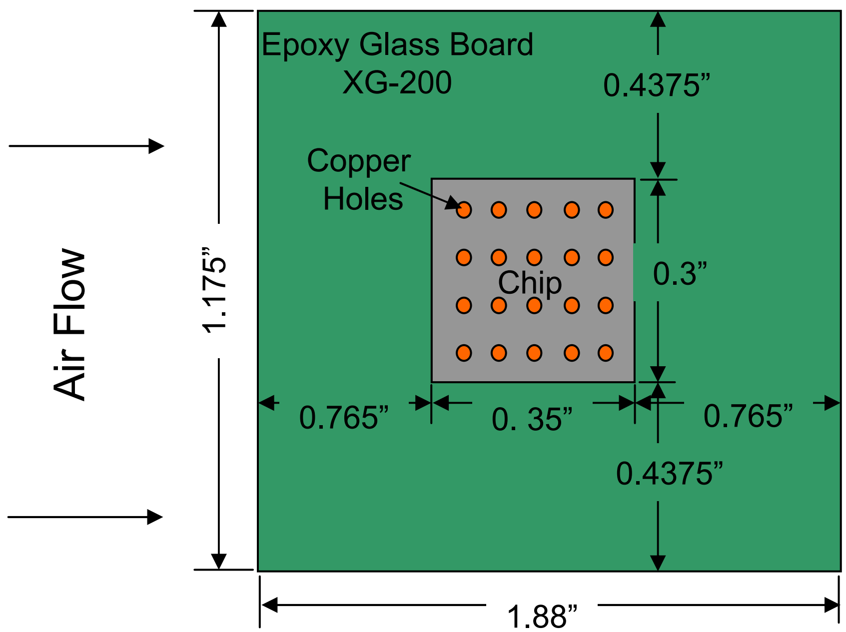
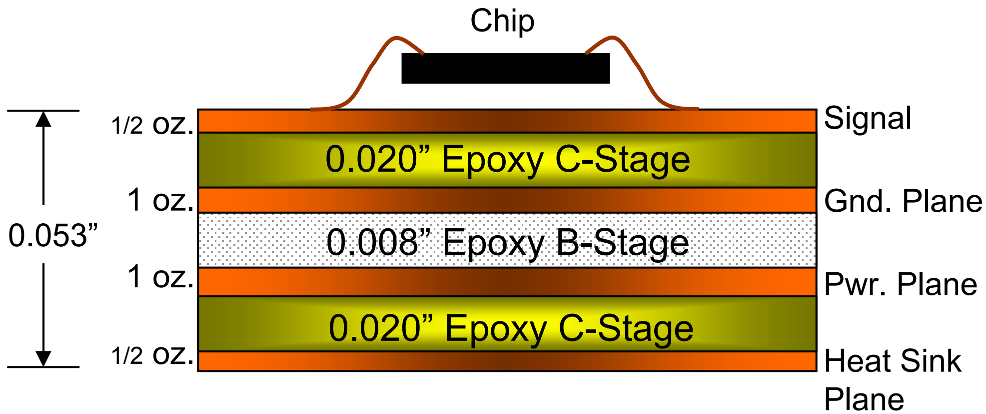
Device-Level Thermal Design

Thermal Vias for Chip on Board Packages:



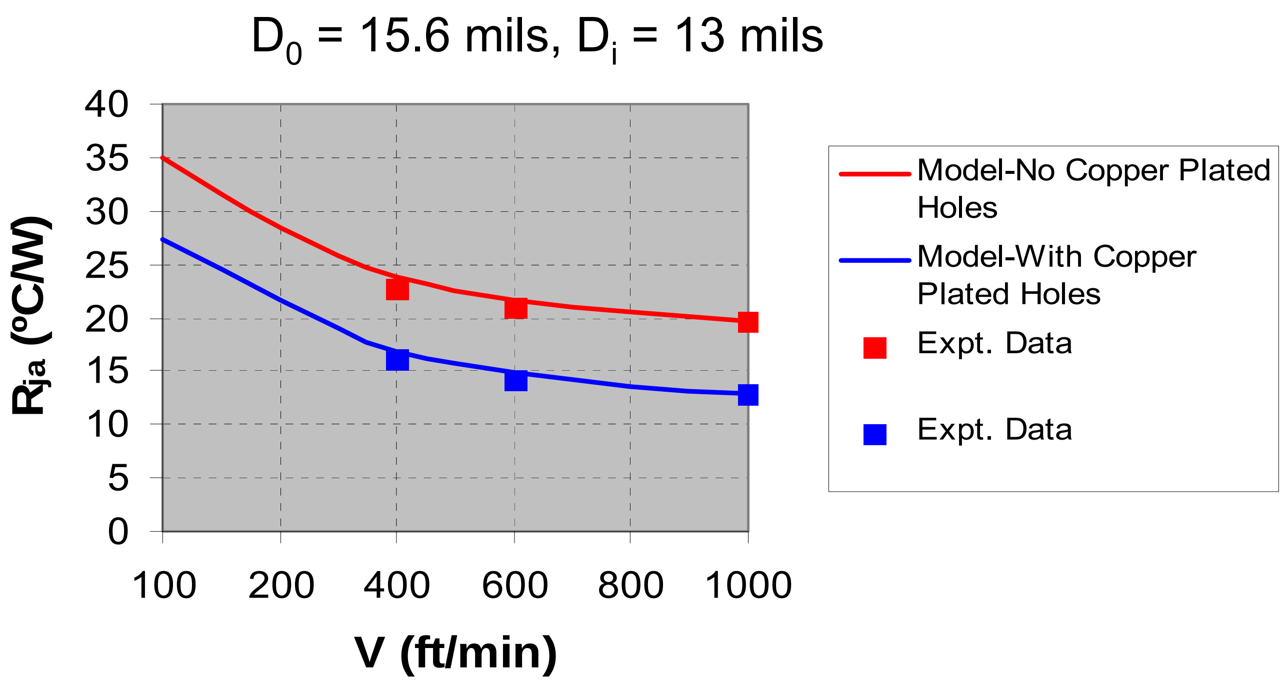
Substrate with Copper Holes



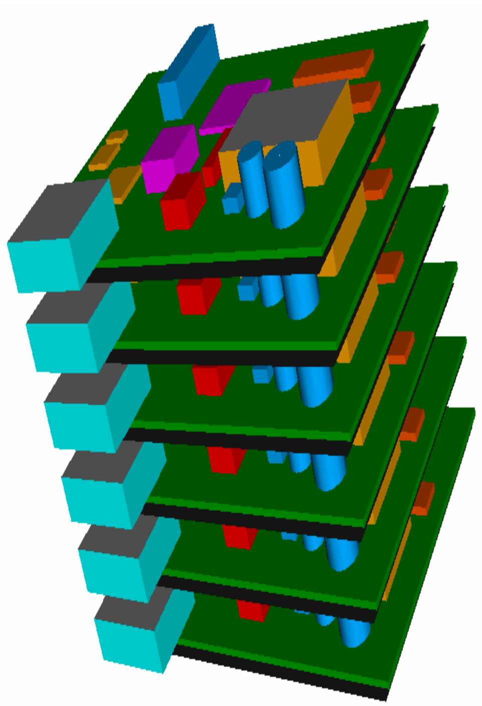
Cross-Sectional View of Package

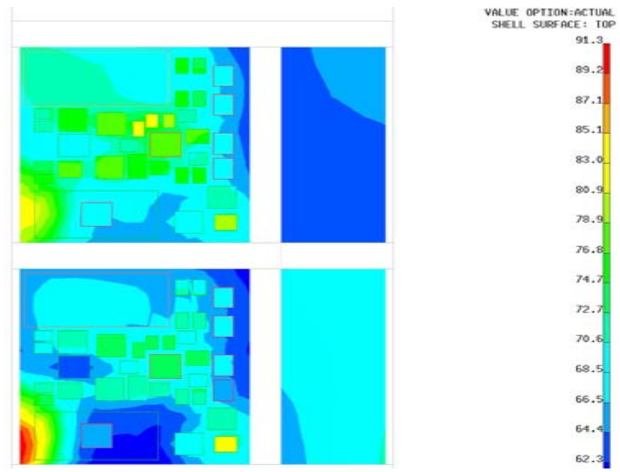
Device-Level Thermal Design

Reduction of IC Thermal Resistance Using Thermal Vias



Thermal Design Considerations of PC Board



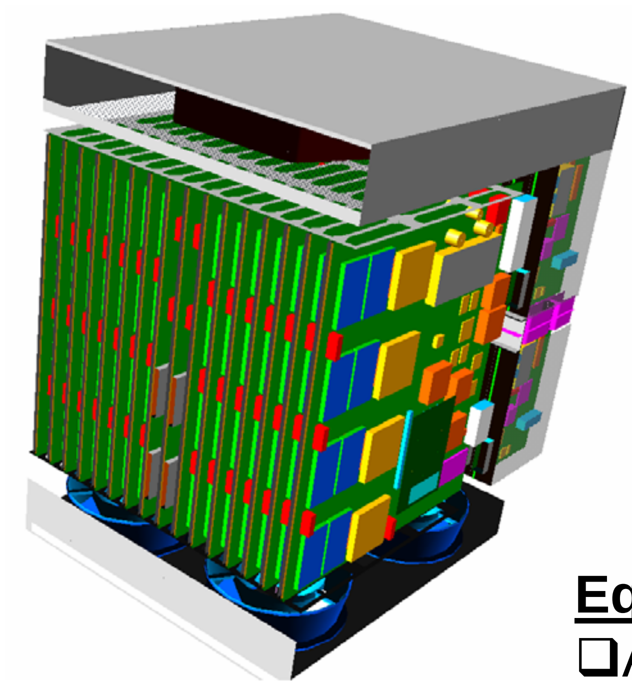


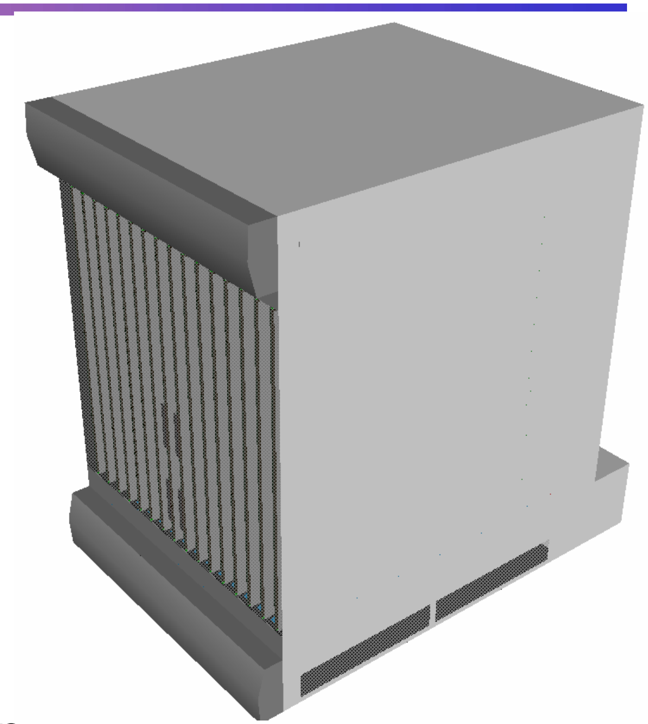
- ❑ Airflow determination
  - ❖ Natural or forced convection
  - ❖ Required amount of airflow
- ❑ Optimize Layout
  - ❖ minimize shadow effect
  - ❖ Locate hotter components in favored areas
- ❑ Heat sinks (Add-on & PCB)
- ❑ Sensors

Air Cooling - Direct Flow Over Boards

- Air Cooling is still the most commonly used,
- Air Flow is provided by fans in forced cooling, or by buoyancy effects in natural cooling,
- Amount of flow and velocity developed in an equipment depends upon the pressure losses,
- Typical orders of magnitude of velocity are:
  - Natural Convection (20 - 50 ft/min, 0.1 - 0.25 m/s)
  - Forced Convection in telecom (300 - 500 ft/min, 1.5 - 2.5 m/s)
  - Mainframe Computers (1000 -1500 ft/min, 5 - 8 m/s)
- *FLOW INSIDE EQUIPMENT IS ALWAYS TURBULENT*

System-Level Thermal Design Considerations

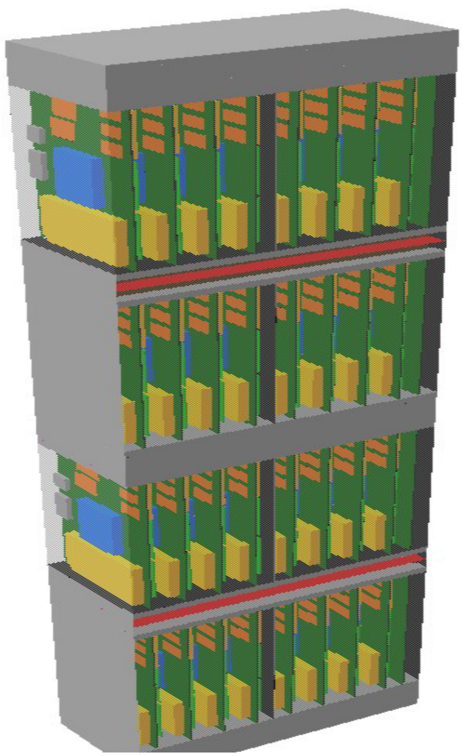


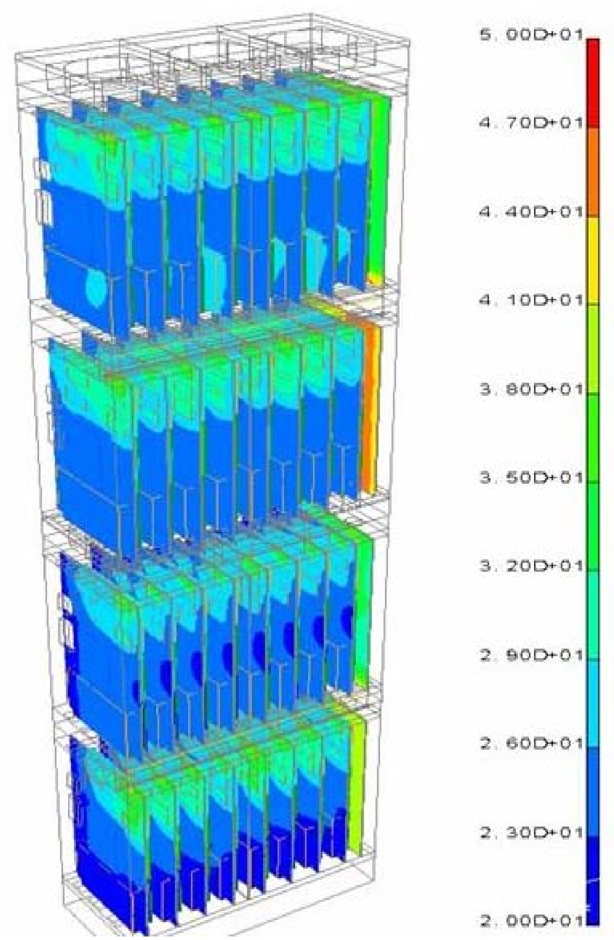


Equipment design

- ❑Airflow/thermal design
- ❑Air intake, exhaust
- ❑Air mover/filter selection
- ❑Fan controller design
- ❑Fan assembly design

Thermal Issues of Single Rack Equipment

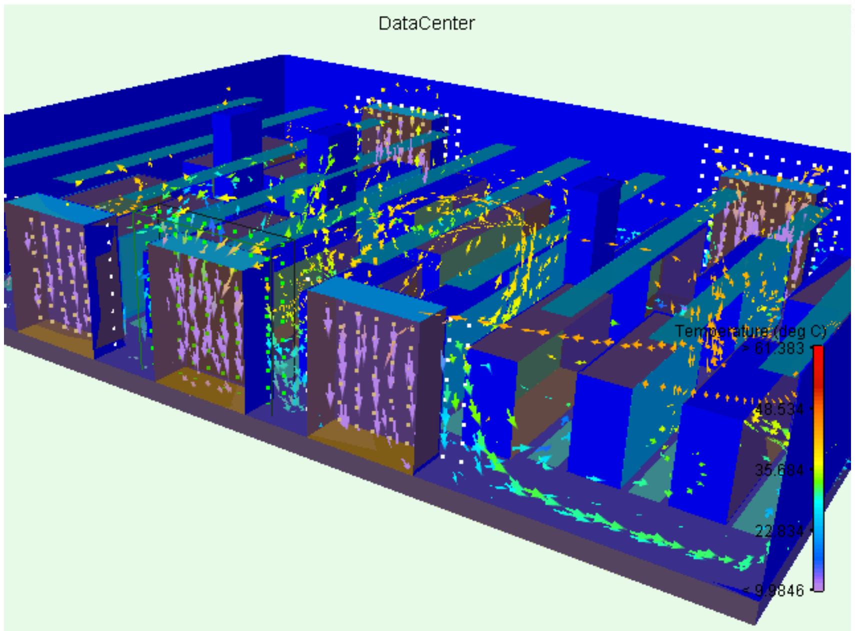


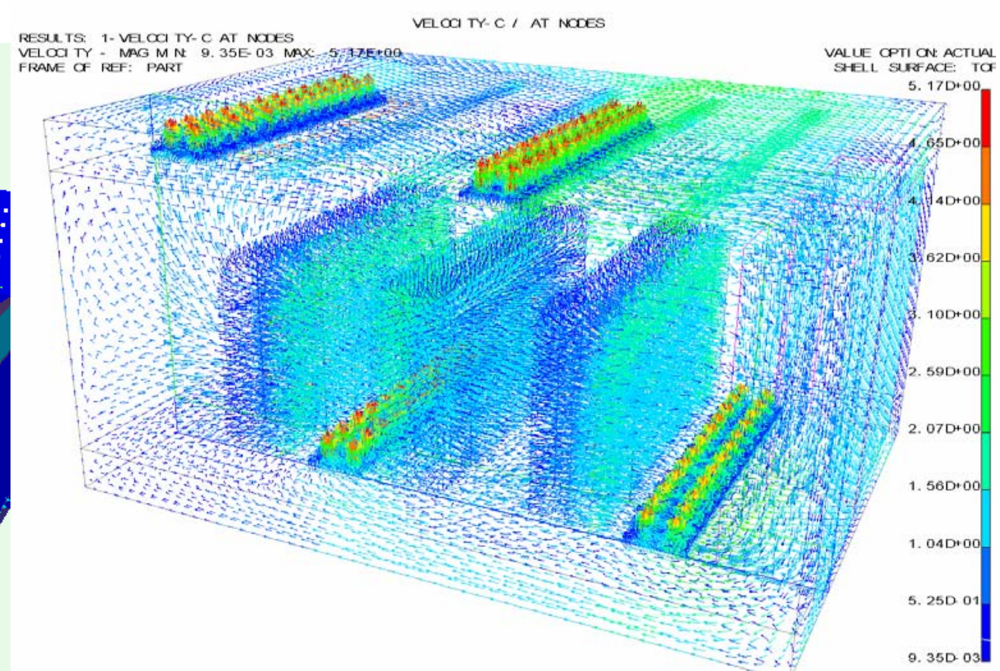


<u>Circuit Bays in Racks with Single Intake & Exhaust</u>

- ❑Effect of circuit bays in a Rack
- ❑Effect of card guides, structures on bays
- ❑Heat rise through bays
- ❑Fan assembly design

Deployment Issues – Room Level Cooling





- ❑Hot Aisle/Cold Aisle
- ❑Airflow Distribution to cold aisles
- ❑Floor layout per heat rack heat dissipation
- ❑Airflow balancing thru the room
- ❑Placement of AC units
- ❑Recirculation of hot air
- ❑Cooling Efficiency
- ❑Equipment Reliability

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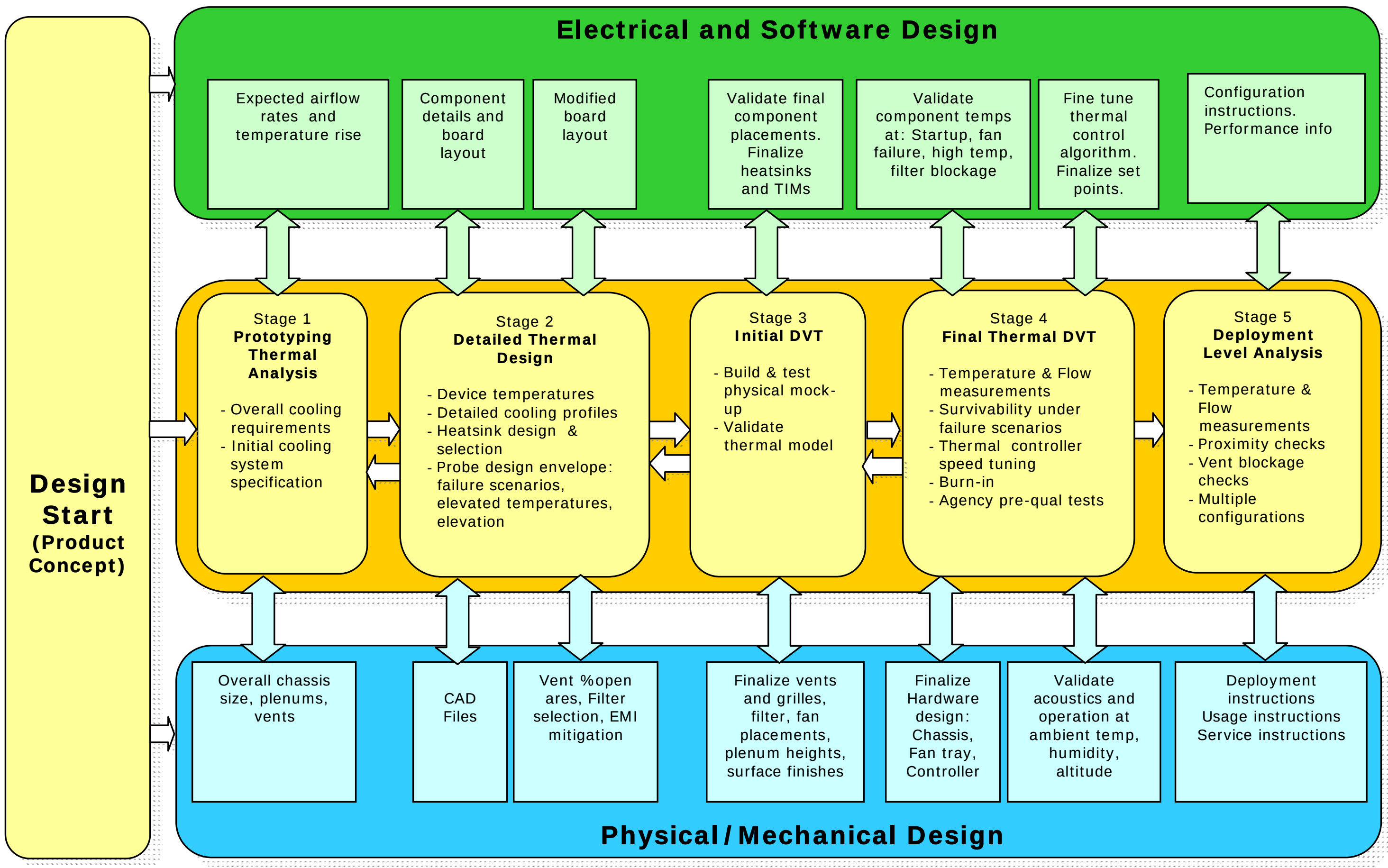
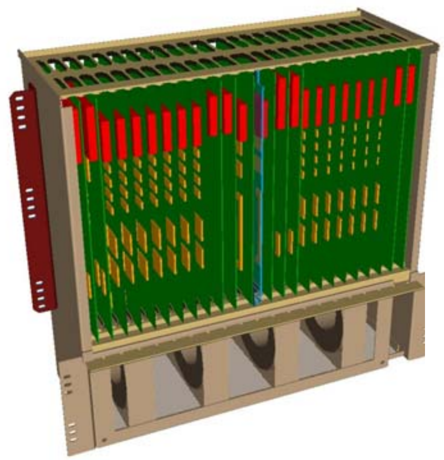
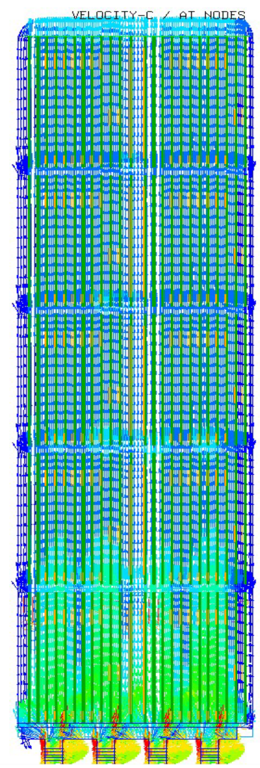
Stages of Thermal Design



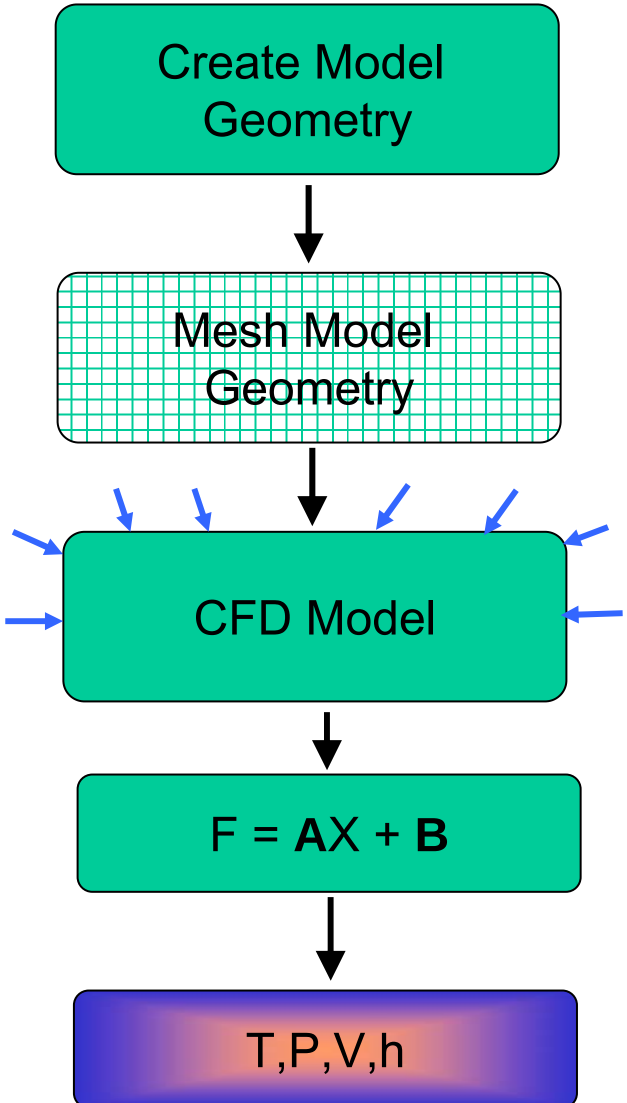
Concurrent Thermal Design

- ❑ Faster time to market
- ❑ Simulate Directly on Design Geometry
  - ❖ Migrate changes quickly to mechanical and electrical designs
- ❑ **Avoid Costly Redesigns**
  - ❖ design must be right first time around
- ❑ **Design to Industry Standards**
  - ❖ NEBS, CSA, CE, etc





Design-Based Thermal Simulation Approach



- Build 3D CFD-CAD Model from Design CAD Models
- Discretize CFD CAD Model
  - Tetrahedral elements for air and solid objects
  - Triangular elements on all convecting surfaces
- Impose initial conditions, boundary conditions and fan curves, rotational motion if applicable
  - Initial conditions are ambient conditions everywhere
  - Boundary conditions are heat loads, ambient (room) conditions
  - Rotational motion is speed of rotation of the rotor in rpm
- Solve CFD model
  - Create control volumes
  - Solve for CFD quantities @ integration points
- Post-Process Results (temperatures, velocities, pressures, heat transfer coefficients, etc)

Thermal Design Starting Points

Specify:

- ❑ Cooling Method (Natural/Forced Convection)
- ❑ Architecture (Push/Pull/Push-Pull)
- ❑ Ambient Temperature Range
- ❑ Quality of Air (Dust, Humidity)
- ❑ Intake and Exhaust Paths
- ❑ Noise Levels
- ❑ Power Budget
- ❑ Servicing Module
- ❑ Repair Time

Experience is a Premium

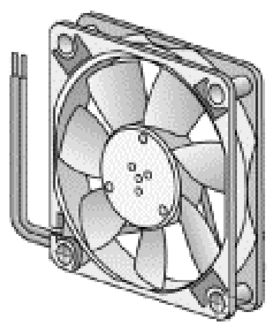
- Develop Simple Engineering Rules to Evaluate Equipment Designs
- Have an Idea of Answers Before Experimentation
- Implement Recovery from Single-point Failures

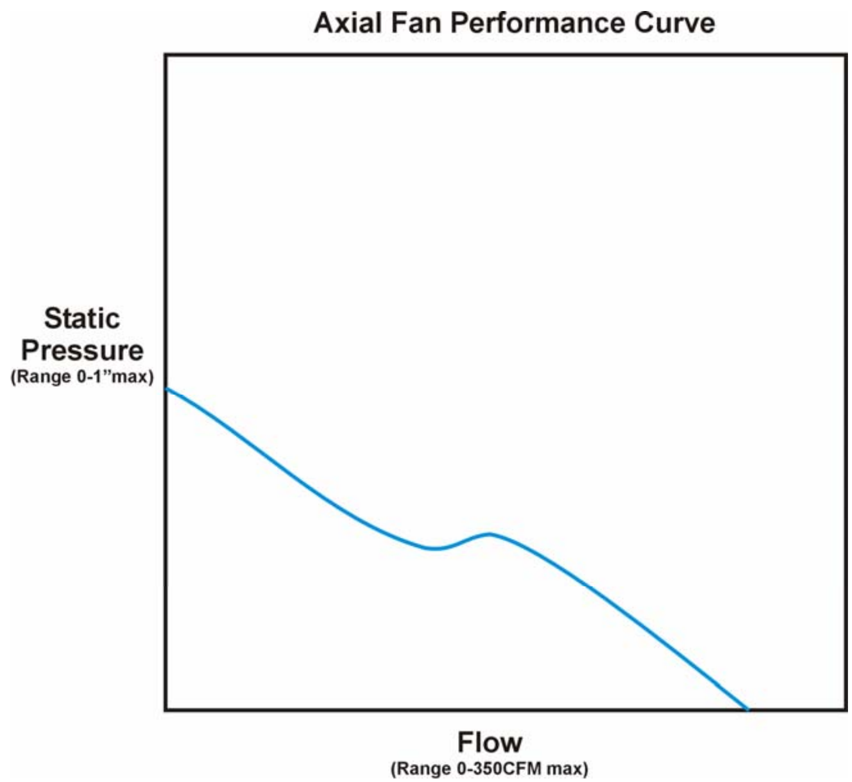
Agenda

- ❑Thermal Trends and Challenges in Electronics Packaging
- ❑Effects of Temperature on Reliability of Electronics Equipment
- ❑Understanding Fans
- ❑Thermal Design Methodologies
- ❑Data Rooms: The next frontier

Fan Types: Tube-axial Fans

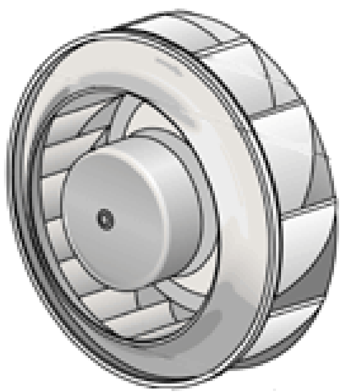
- ❑Inexpensive
- ❑More suppliers
- ❑Pressure capabilities are limited in high impedance systems.
- ❑Ideal for low impedance applications.

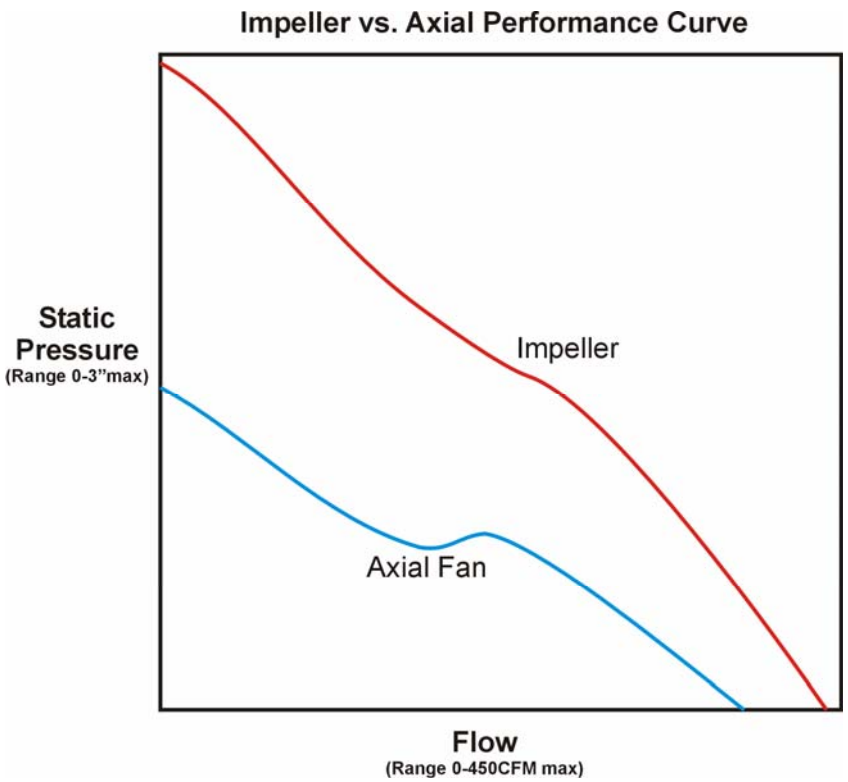




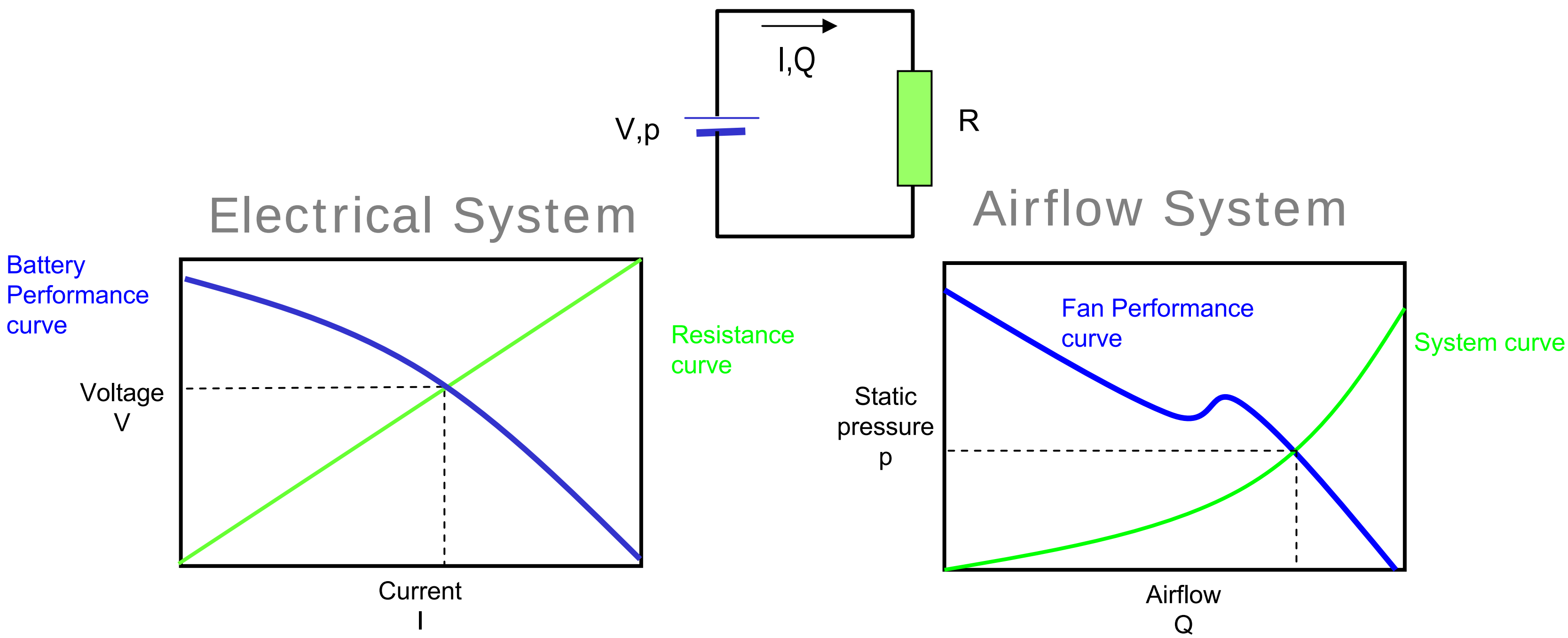
Fan Types: Impellers (Radial)

- ❑High impedance high flow
- ❑Ideal for Pull systems due to natural 90° turn.
- ❑Pressure capabilities are very good.
- ❑Fan spacing is limited due to flow path.

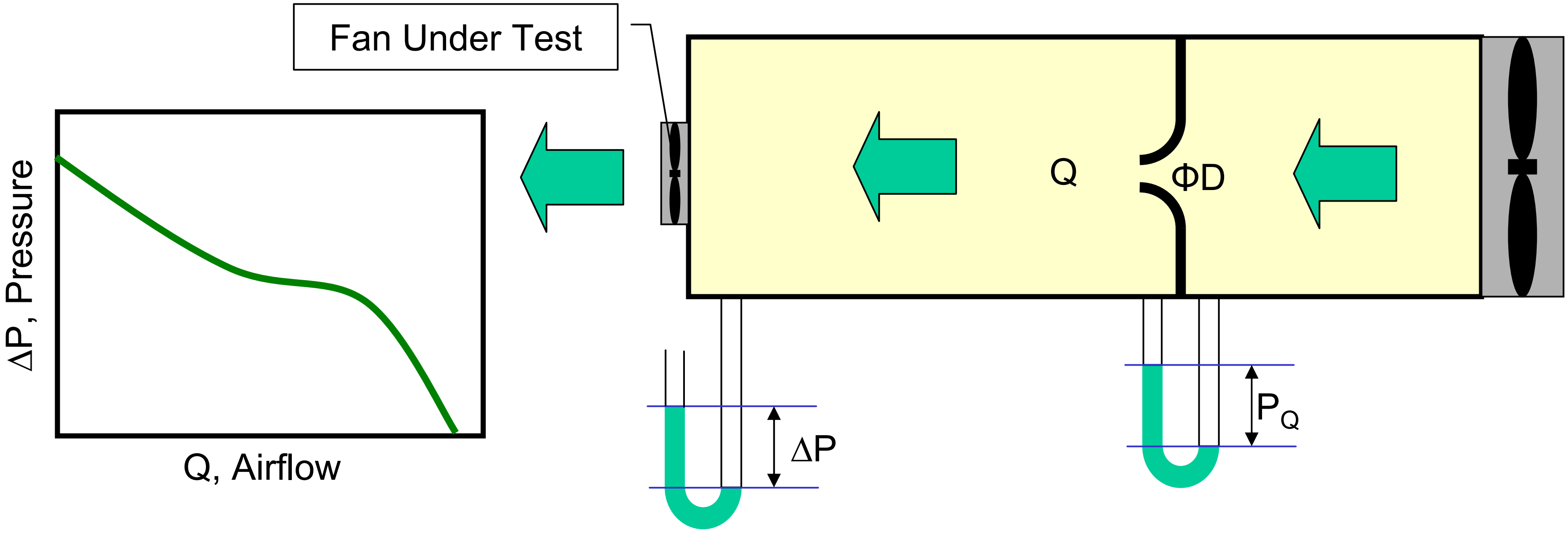




Fan Performance and System Resistance



Determining Pressure-Flow Curve of a Fan



- Change ΔP from 0 to max (zero flow) by adjusting tunnel flow
- Measure P_Q and calculate Q, gross airflow
- Plot Q-ΔP curve

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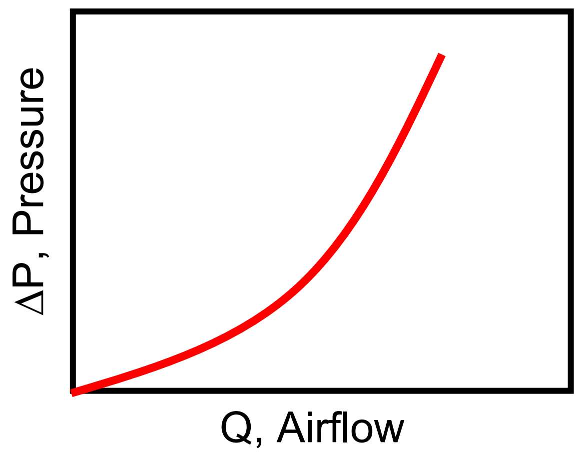
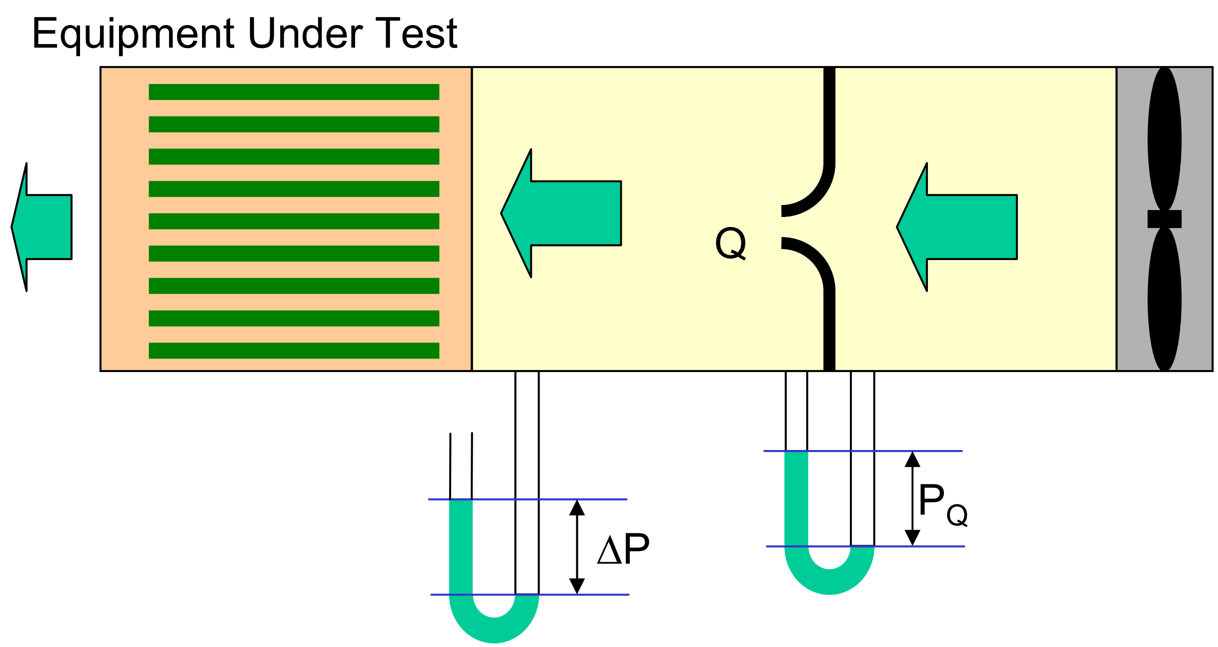
Determining System Resistance Curve of Equipment





- Change ΔP from 0 to max (zero flow) by adjusting tunnel flow
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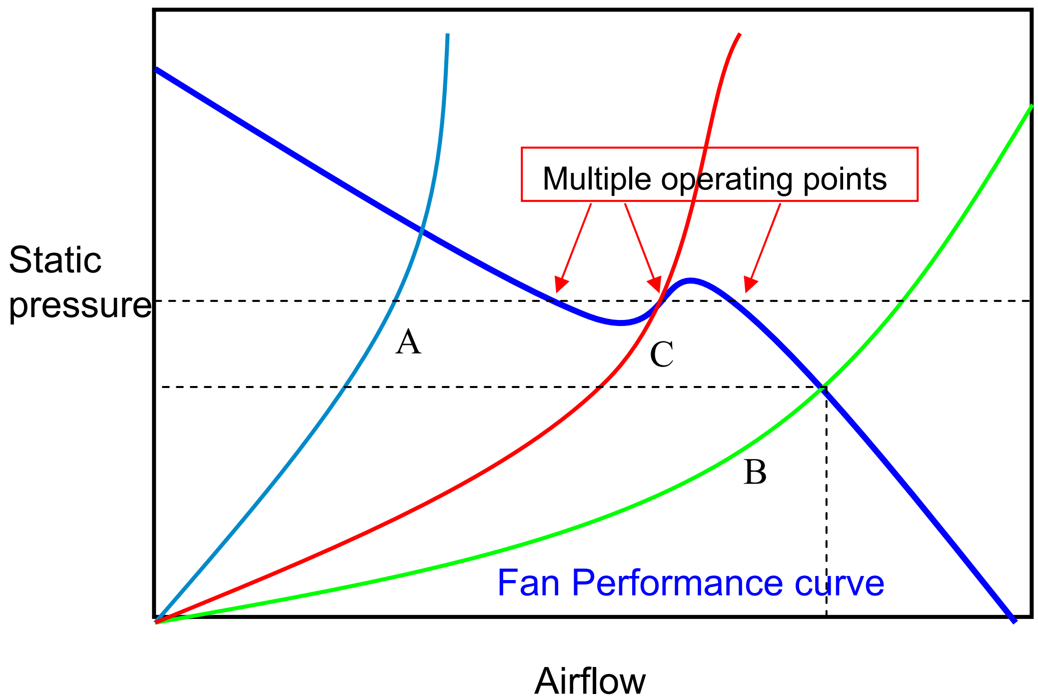
Selection of the right fan and the Operating Point



Operating Point: A
- **Low Airflow**
- **Inefficient Performance**
- **High Noise Level**

Operating Point: B
- **High Airflow**
- **Efficient Performance**
- **Low Noise Level**

Operating Point: C
- **Multiple Operating points for same pressure**
- **Fan speed hunts between the operating points**
- **Inefficient Performance**
- **High cyclic Noise Level**
- **Significant reduced fan life**

Smart Design Offer Major Gains

- Can we simply increase airflow as power increases?
- What are the cost implications?
- Here is a quick summary.

FAN LAWS

Fan performance is measured in terms of

Pressure ΔP ,volume flow rate (Q), and power absorbed (W)

These are dependent upon a number of factors

(1) type of fan (tube axial, vane axial, blower)

(2) operating point on the fan curve, DP vs Q

(3) size of fan (diameter D)

(4) speed of rotation (N, rpm)

(5) density of gas or air (ρ)

FAN LAWS

By considering a point of operation on fan curve

It is possible to derive some simple scaling laws

Between ΔP , Q, W, D, N, and ρ for a fan

Such as

$$Q = \mathbf{F_1} (D, N)$$

$$\Delta P = \mathbf{F_2} (D, N, \rho)$$

$$W = \mathbf{F_3} (D, N, \rho)$$

These Functional Relationships Are Called "FAN LAWS"

Airflow

From dimensional analysis we obtain FAN LAWS as

(1) $Q \alpha D^3 N$

From (1), Q is independent of density. therefore

fan at sea level or say 2000m. has same Q capacity.

But Fan Mass Flow Rate ($= \rho Q$) varies with altitude.

Also from (1), Q varies linearly with N

Pressure and Power

(2) Differential Pressure

$$\Delta P \propto D^2 N^2 \rho$$

(3) Pumping Power,

$$W \propto D^5 N^3 \rho$$

From (1), (2), and (3),

$$W \sim Q \cdot \Delta P$$

(Ignoring all electrical efficiencies)

Sound Pressure

Sound Power Level S has the functional relationship

(4) $S \quad \alpha\ Q\ DP^2,$

$\alpha\ (D^3 N)(D^2 N^2 q)^2$

$\alpha\ D^7 N^5 \rho^2$

For a given D and ρ,

$S\ \alpha\ N^5$

Fan Noise Is Very Strongly Dependent on Speed N

Design Implications

Let us understand the engineering implications of these 4 fan laws for Q, ΔP, W and S

For a given fan we want to increase Q by 25 %

What are the implications?

From (1), To Increase Q by 25%, increase N by 25%

Design Implications

From (3), Fan Pumping Power W increases by

$$1.25^3 = 1.95,$$

that is an increase of 95% in fan power

From (4), fan sound power level S increase is

$$1.25^5 = 3.05,$$

that is an increase of 305% in noise power S

Design Implications

Fan Sound Law (4) can be expressed in dB form as change in sound power level from speed N1 to N2 as

ΔdB = dB(N2)-db(N1)
=10 log(N2/N1)5

=50 log(1.25)

= 4.85

(5 dB difference in sound level is noticeable)

A Comparison

Results are tabulated for N2 = 1.25 N1 and N2 = 2 N1

N2/N1	Q2/Q1	ΔP2/ΔP1	W2/W1	dB21
1.25	1.25	1.56	3.05	4.85
2	2	4	8	15

Nutshell

- Heat Transfer Coefficient $h \alpha V^{0.7}$. So doubling N increases h by 62%
- To remove 62% more heat, airflow should be doubled

  Q2 = 2*Q1 OR N2 = 2*N1
- Doubling flow causes ΔP to increase by a factor of 4

  ($\Delta P \alpha V^2$)
- Power required to double airflow is W2 = 8* W1
- Sound level increases by 15dB
- Fan bearing life deteriorates rapidly with higher speed N. Therefore fan life deteriorates drastically.

Nutshell

- Increasing flow rate beyond a certain value is not worthwhile
- This is “Murphy's law" for electronic cooling
- Optimize your design (heat removed/pumping power)
- “Smart Thermal Engineering”
- This observation is true for cooling devices, boards, chassis or data rooms.

Cost Implications

- Expensive, High performance fan
- Larger Power Supply
- Lower Life
- Acoustic and electrical noise filtering

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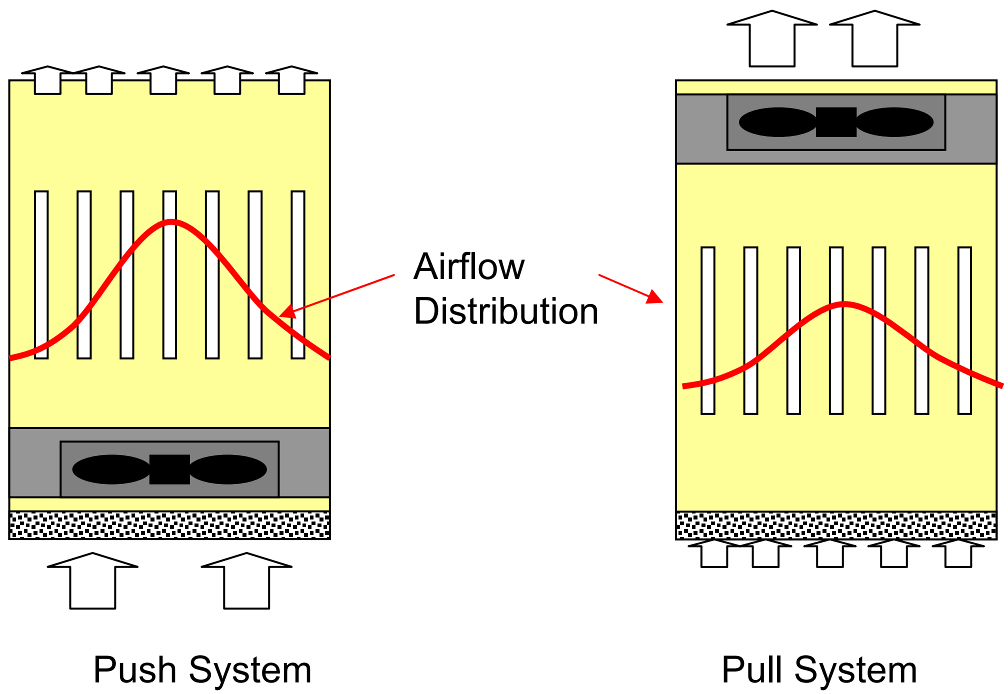
Thermal Design Methodologies

- Design Process
- Architectures
- Failure detection and recovery
- Designing for Reliability
- Design validation- Testing

Fan Placement - Push vs. Pull System



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System-Level Thermal Architecture

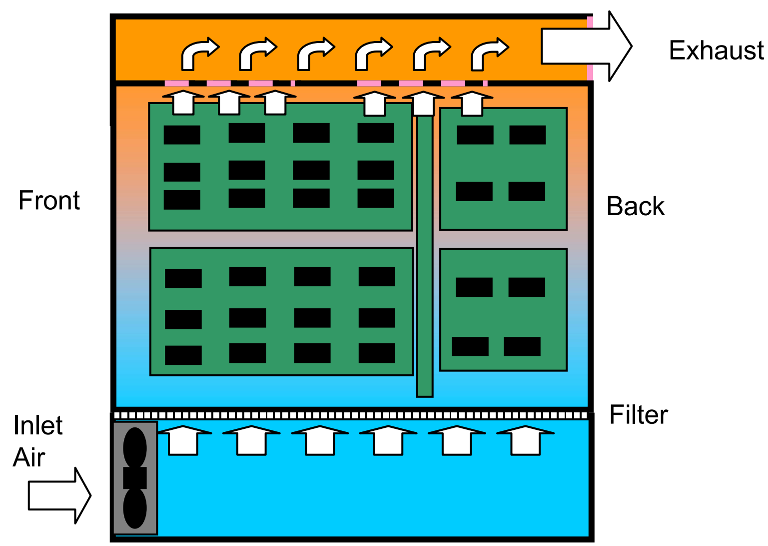
Push Design

Pros:

- ❑ Pressurized system - clean air
- ❑ Low fan operating temperature

Cons:

- ❑ Filter often too close to the fan
- ❑ Localized filter usage
- ❑ Non-uniform air flow
- ❑ Air leakage
- ❑ Need for flow deflectors



degree°C™

Engineered Airflow. Intelligent Cooling.

System-Level Thermal Architecture

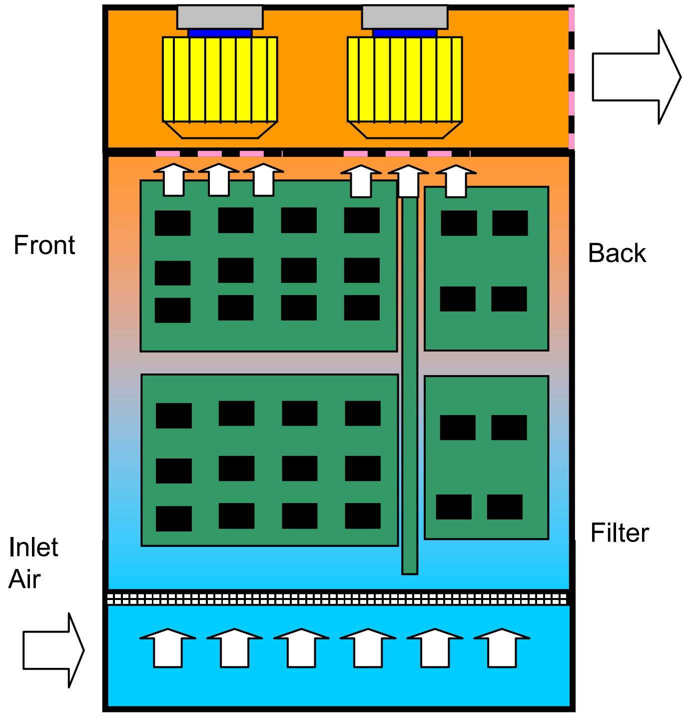
Pull Design with Radial Fans

Pros:

- ❑ Can handle high pressures
- ❑ High flow performance
- ❑ Exhaust direction change
- ❑ Lower recirculation on fan failure

Cons:

- ❑ Low fan density - Large flow drop on fan failure
- ❑ Expensive
- ❑ Unfiltered air leakage



Engineered Airflow. Intelligent Cooling.

System-Level Thermal Architecture

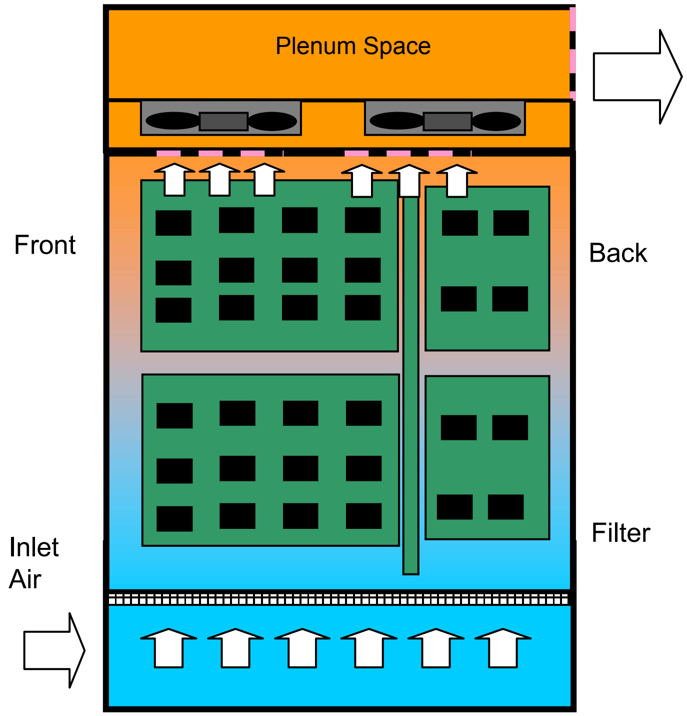
Pull Design with Axial Fans

Pros:

- Cheaper fans
- Better flow uniformity
- Filter usage efficiency

Cons:

- Requires plenum space on top
- Performance loss due to flow turn
- Loss of a fan leads to large recirculation
- Overall (fan + plenum) height is comparable to radial fan model
- Fan at high temperature



System-Level Thermal Architecture

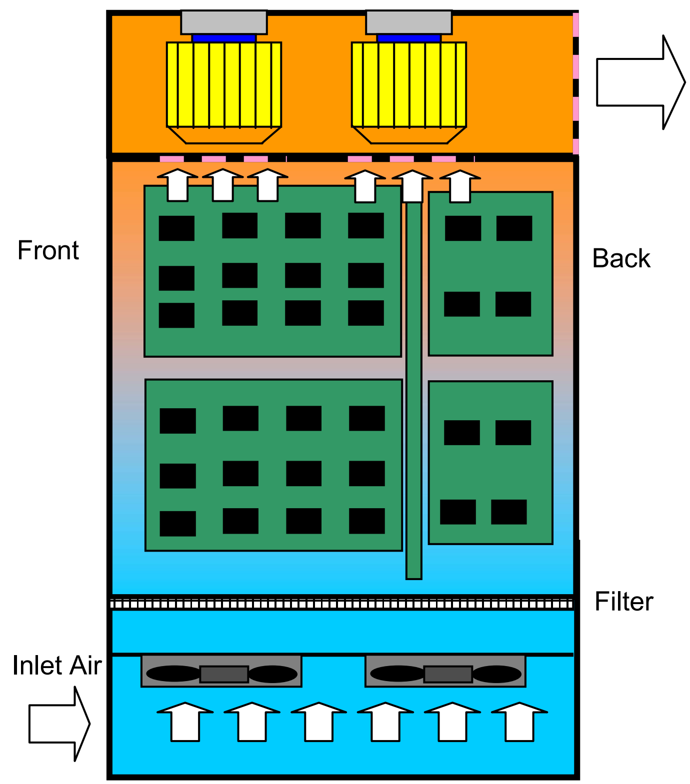
Push-Pull Design

Pros:

- Better control over air flow
- Fault Tolerant/ High reliability
- Division of pressure (smaller fans)
- High Pressure capacity

Cons:

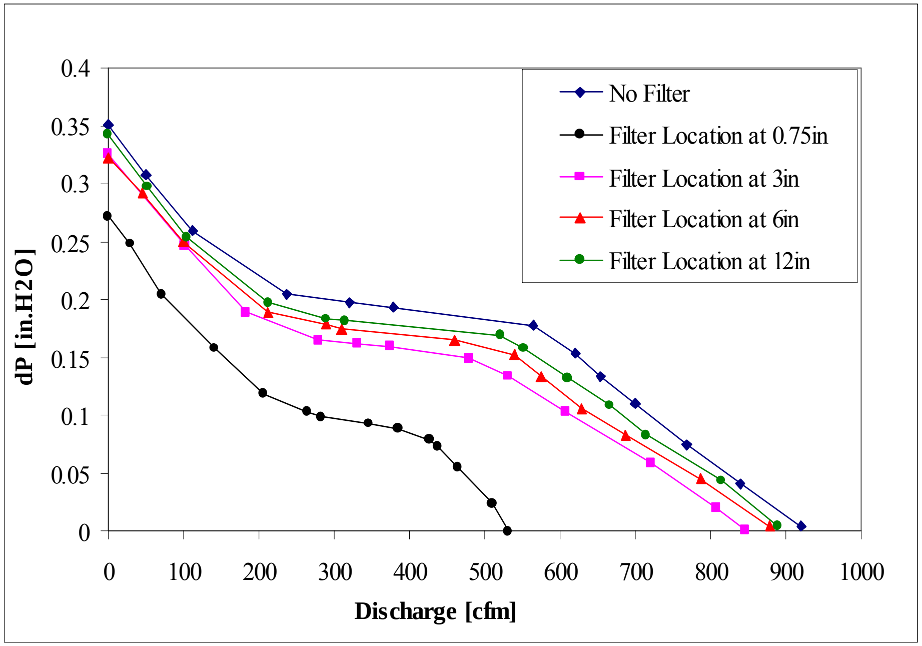
- Expensive

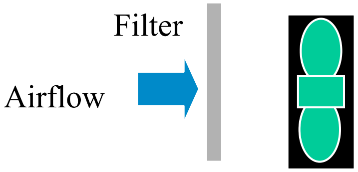


Effect of Fan to Filter distance

Upstream Filter Installation:

- Filter degrades fan performance
- Performance degradation increases as the filter is moved closer to the fan
- Pull systems with filter installed at the inlet yields best results
- Fans see filtered air

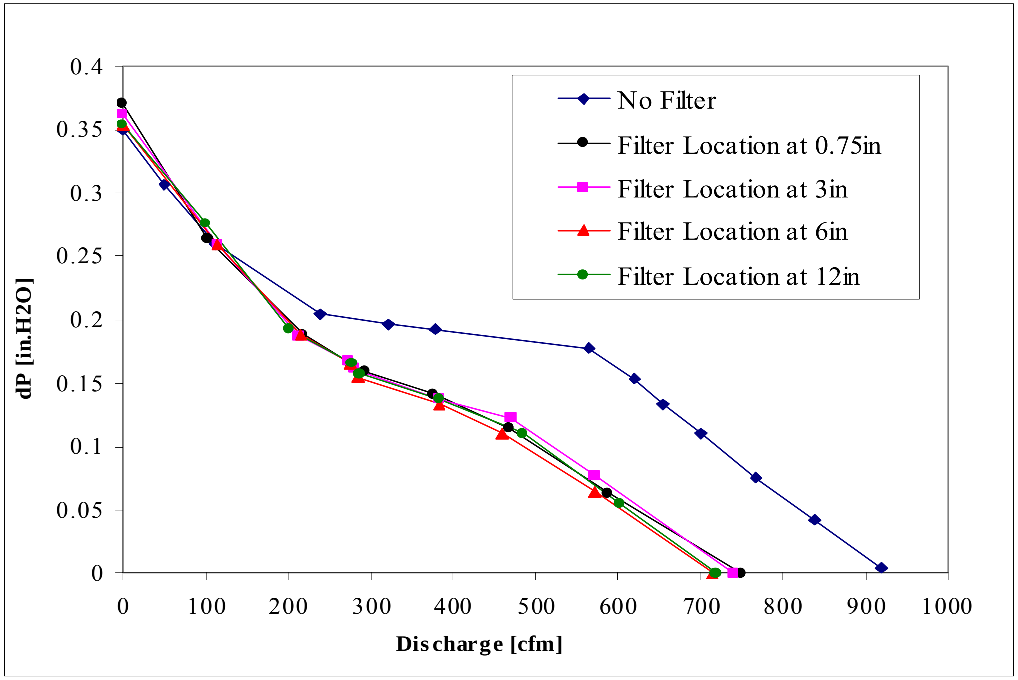


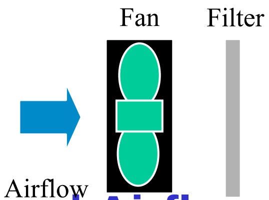


Effect of Fan to Filter distance

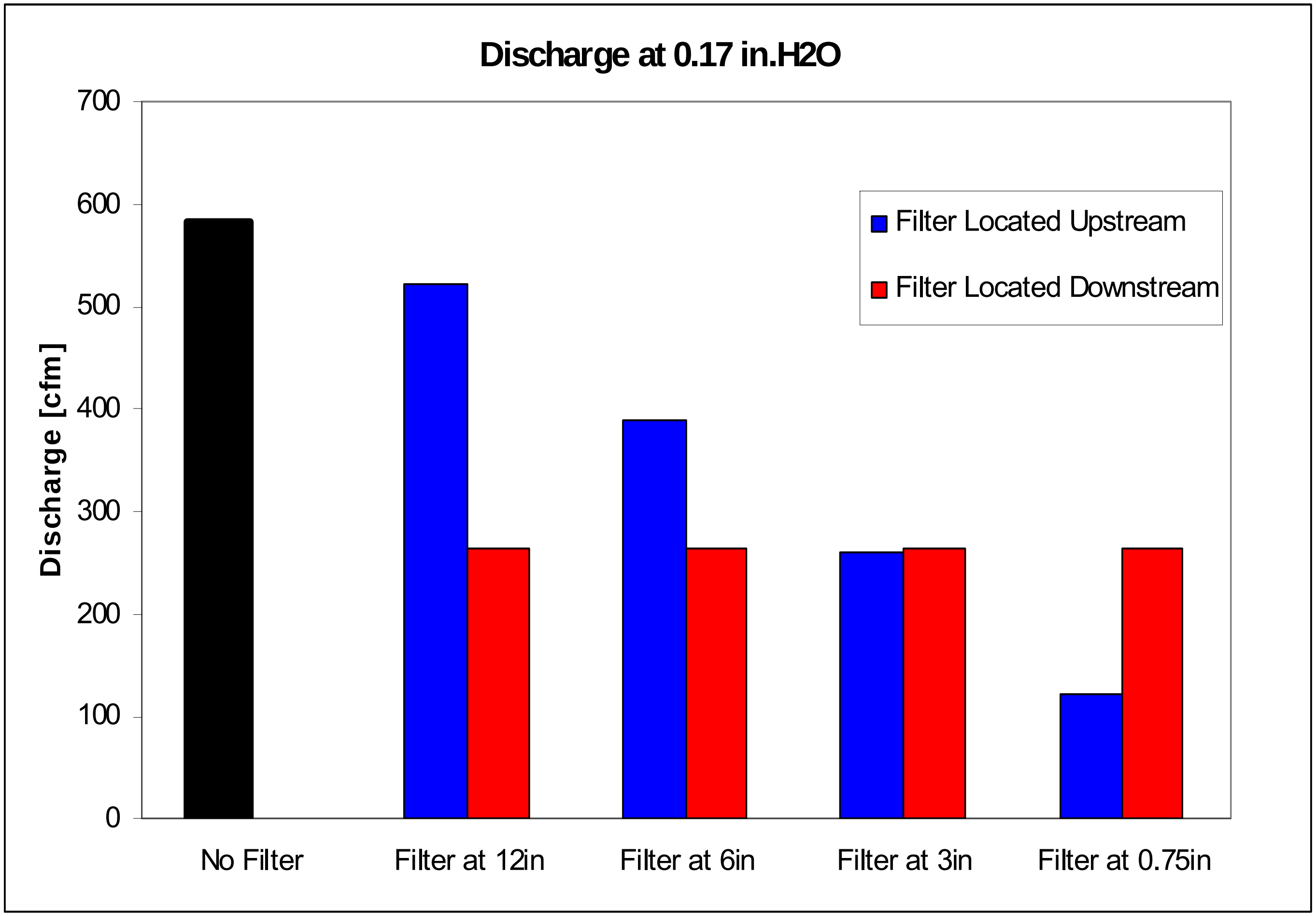
Downstream Filter Installation (Push Designs only):

- Filter degrades fan performance
- Filter location does not affect fan performance
- Cannot be used for Pull system
- Fan sees unfiltered air

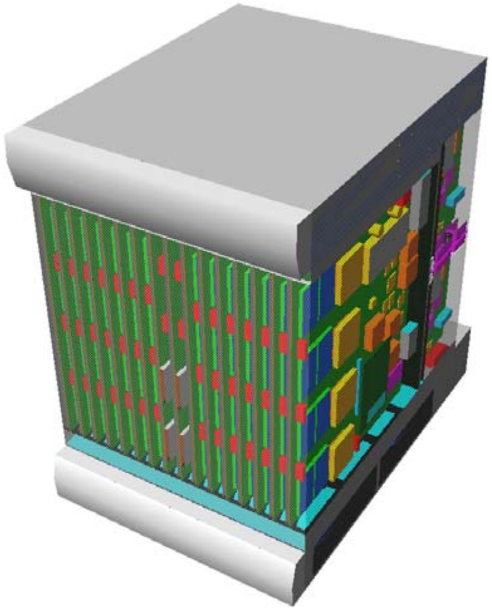


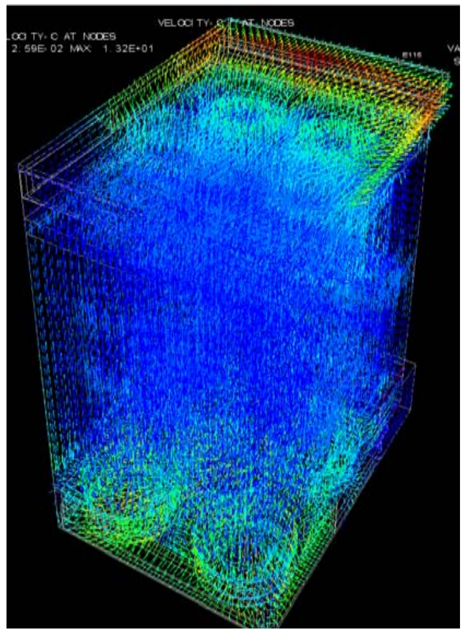


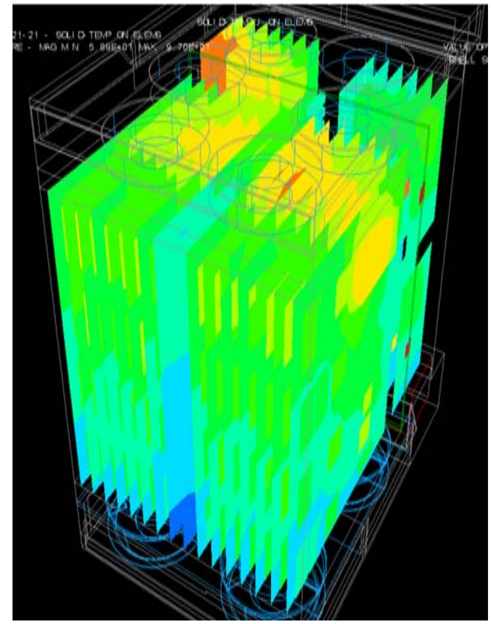
Effect of Fan to Filter distance



Airflow and Thermal Simulation

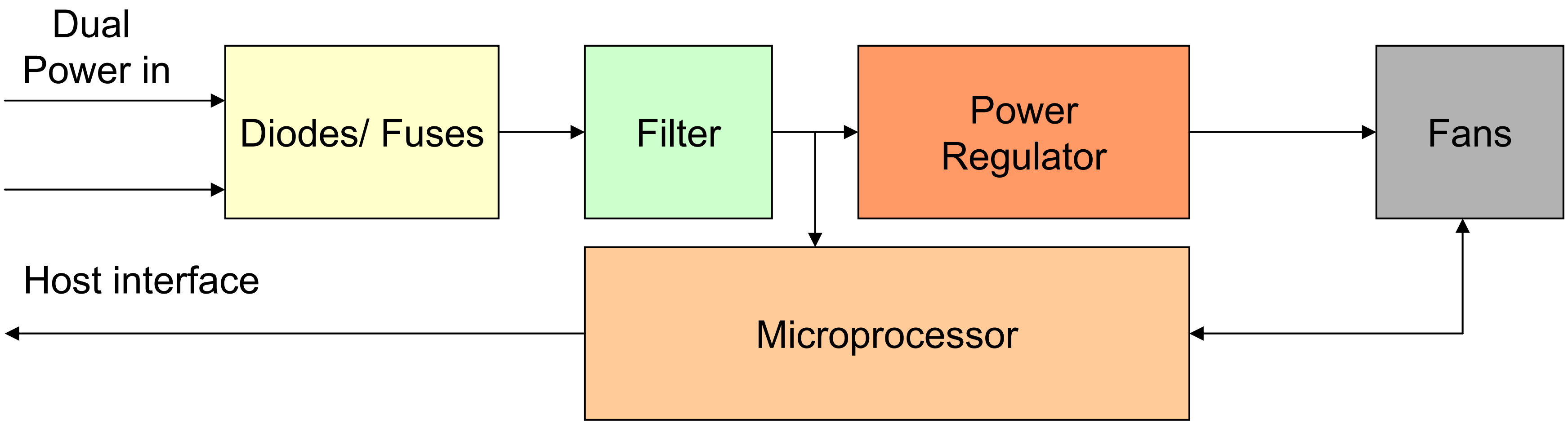






- Computer simulation help eliminate most thermal problems
- Assumptions very key to result quality (Experience Vs CFD)
- Test “What-If” conditions
- 20% accuracy of simulation to test results is acceptable

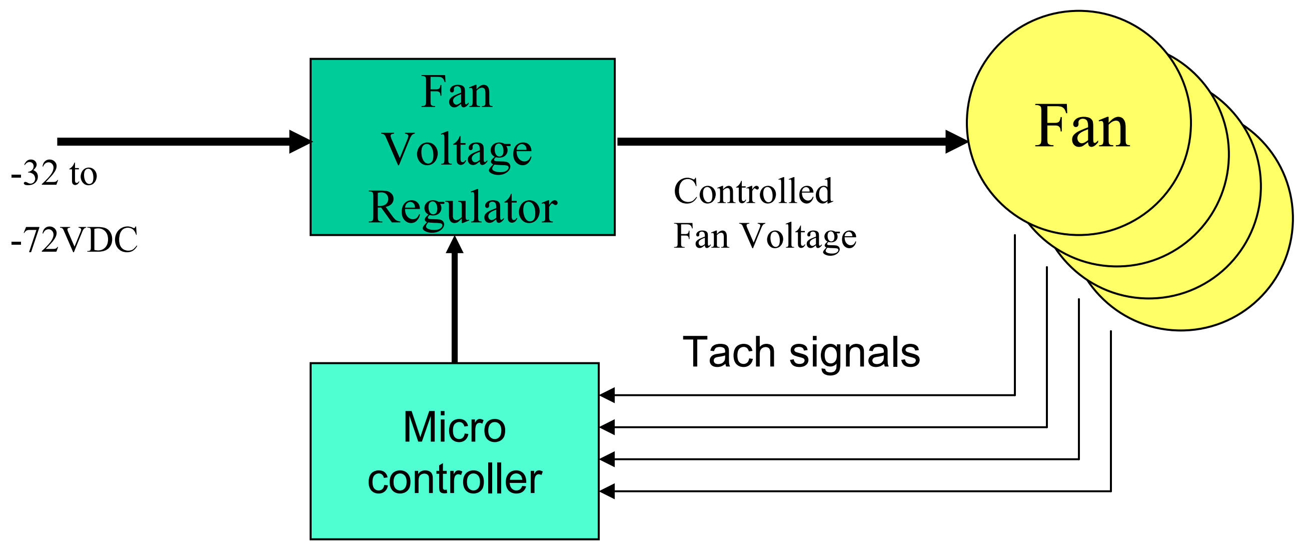
Blocks of a Cooling Management System



Typical thermal management system consists of fans, controller, power regulator

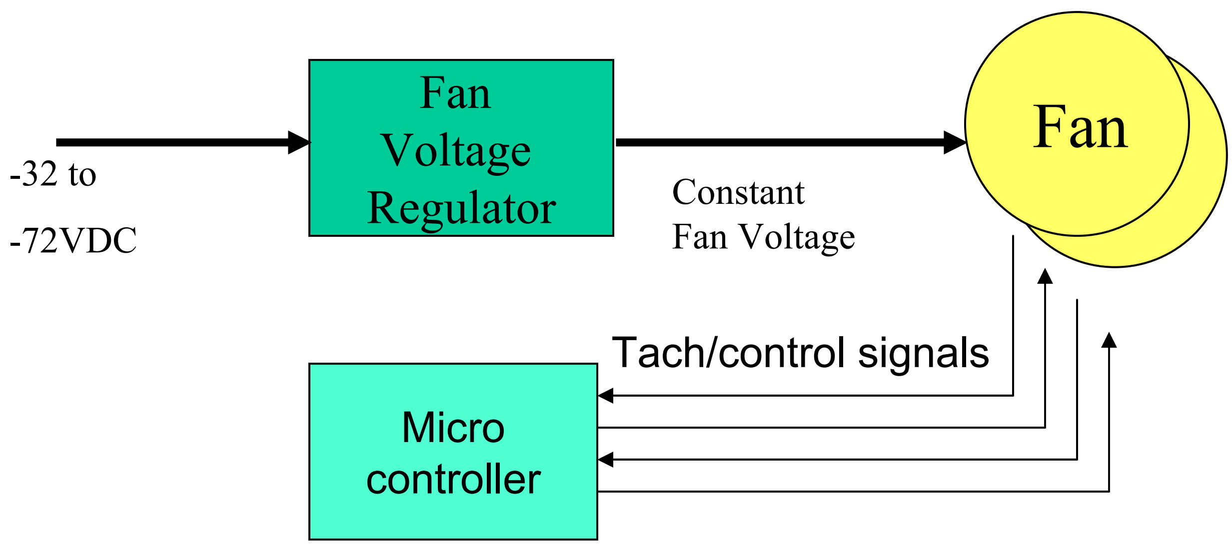
Fan Types: 3 Wire

- Tachometer signal (TTL, Open Collector)
- Speed control through fan voltage change
- No individual speed control possible



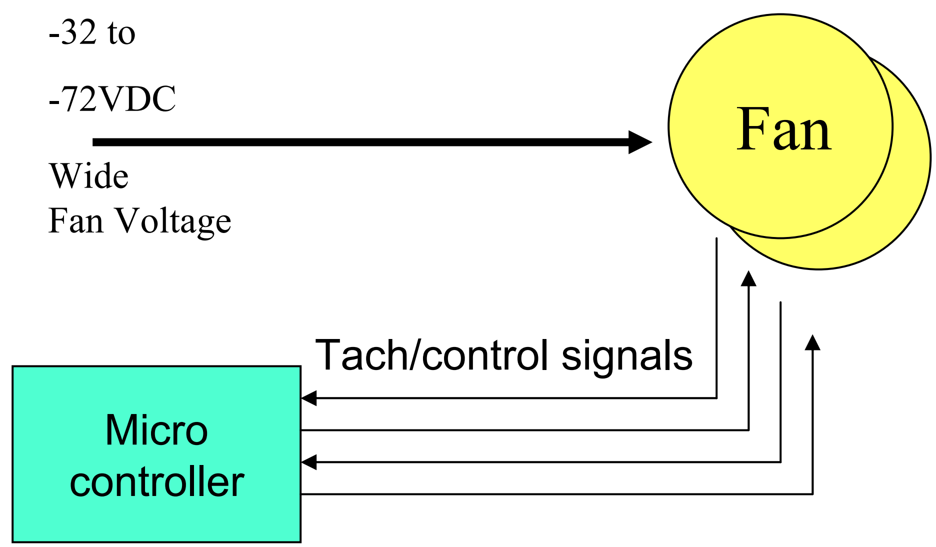
Fan Types: 4 Wire

- Control Input Signal (Analog, PWM)
- Tach output signal
- Speed control through Control signal
- Precise individual speed control possible



Fan Types: Wide Voltage Input

- 32-72VDC (No power regulation required)
- Internally regulated voltage
- Expensive

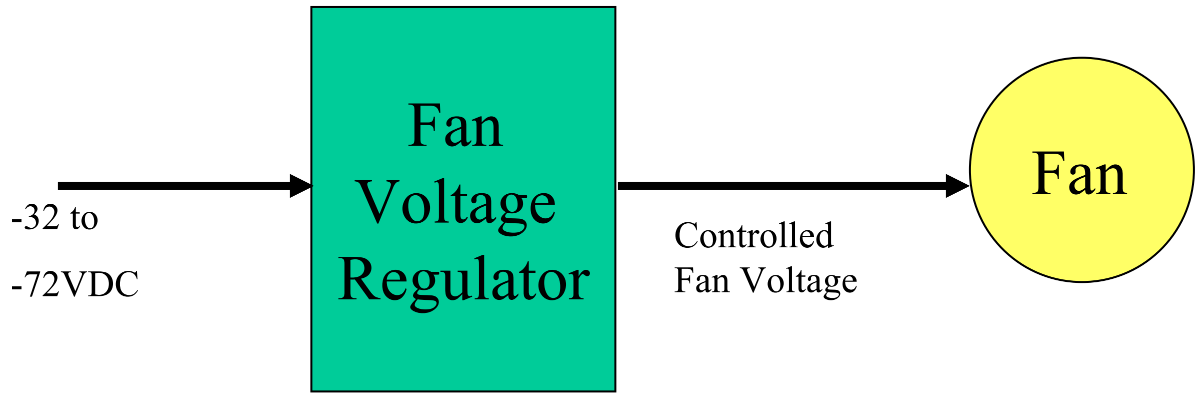


Power Architecture (Telecom application)

- ❑ Input range of –32 to -75VDC
- ❑ Fault Tolerant design
- ❑ Hot Plug-in
- ❑ Inrush current suppression
- ❑ Low switching noise
- ❑ Commutation noise suppression

Need for a Voltage Regulator

- ❑ Low input voltage: Low airflow
- ❑ High Voltage: Fan damage
- ❑ Hence need for fan voltage regulation



Power Architecture

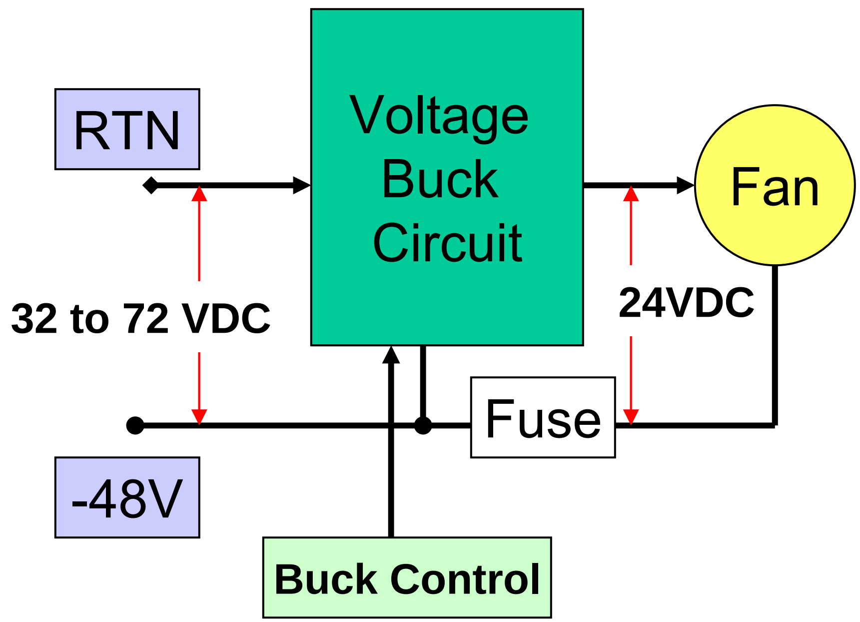
Voltage Buck Regulator 1: Negative Referenced

Pros:

- High switching efficiency
- Availability of 24V fans
- Control and Switching circuits have same reference

Cons:

- Referenced to HOT input line
- Fusing should be on Negative line
- High load current, large switching power devices



Power Architecture

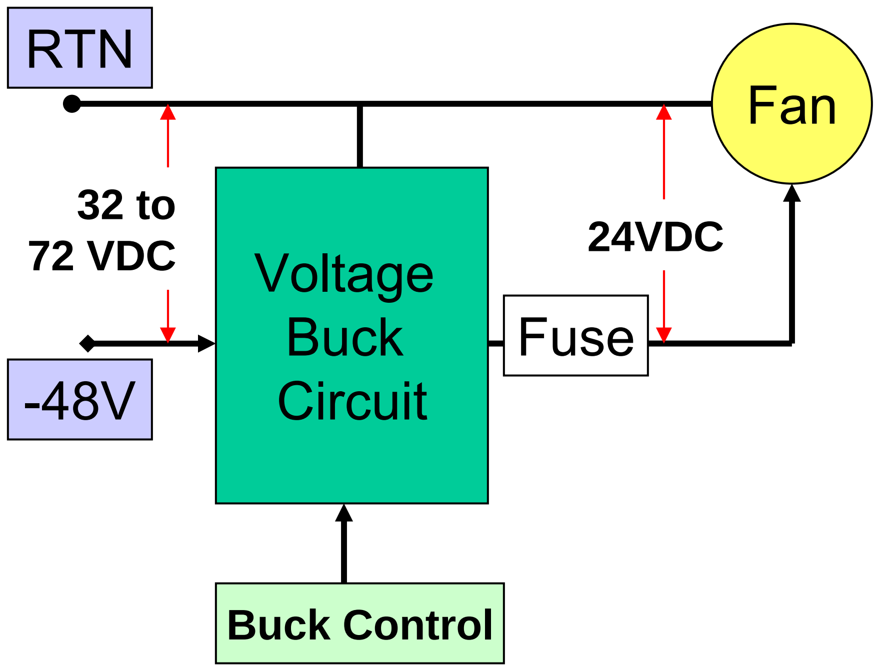
Voltage Buck Regulator 2: Positive Referenced

Pros:

- High switching efficiency
- Availability of 24V fans
- Referenced to input RETURN line

Cons:

- Fusing should be on Negative line
- Control and Switching circuits have different reference
- High load current, large switching power devices



Power Architecture

Voltage Buck-Boost Regulator 2

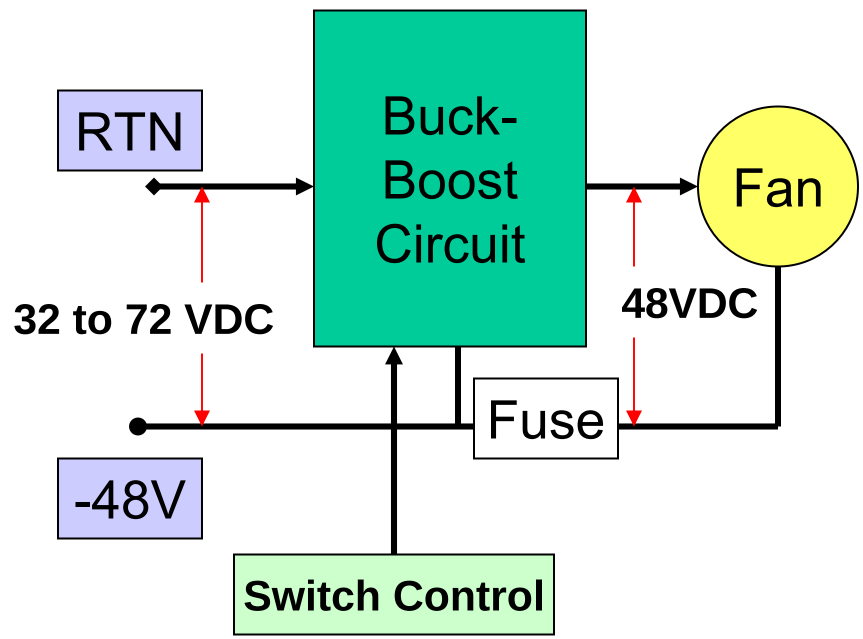
Fan Voltage generated through self running Buck Boost converter

Pros:

- ❑ High switching efficiency
- ❑ Control and Switching circuits have same reference
- ❑ Does not need micro controller

Cons:

- ❑ Fusing on Negative line



Power Architecture

Voltage Boost Regulator

Boost Converter:

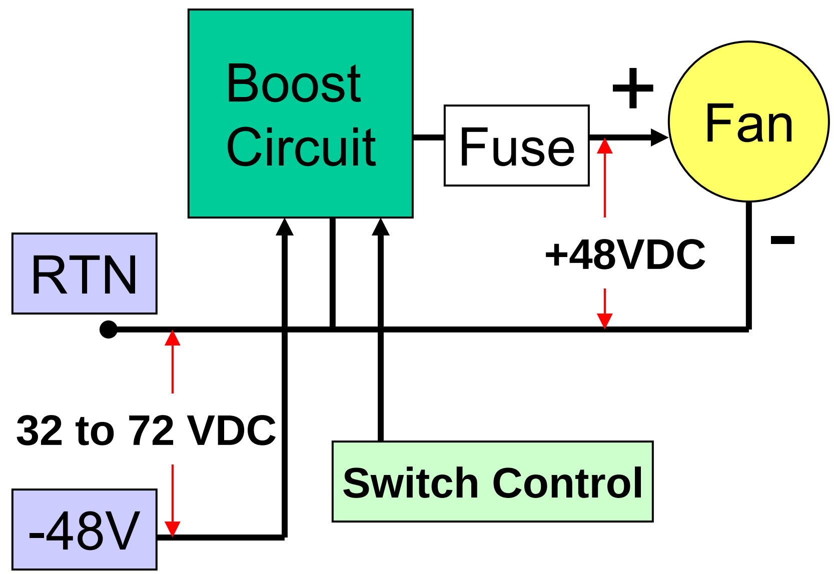
Converts –48V into controlled positive fan voltage referenced to RETURN.

Pros:

- Referenced to input RETURN line
- Low conducted commutation noise
- Fusing on Positive line

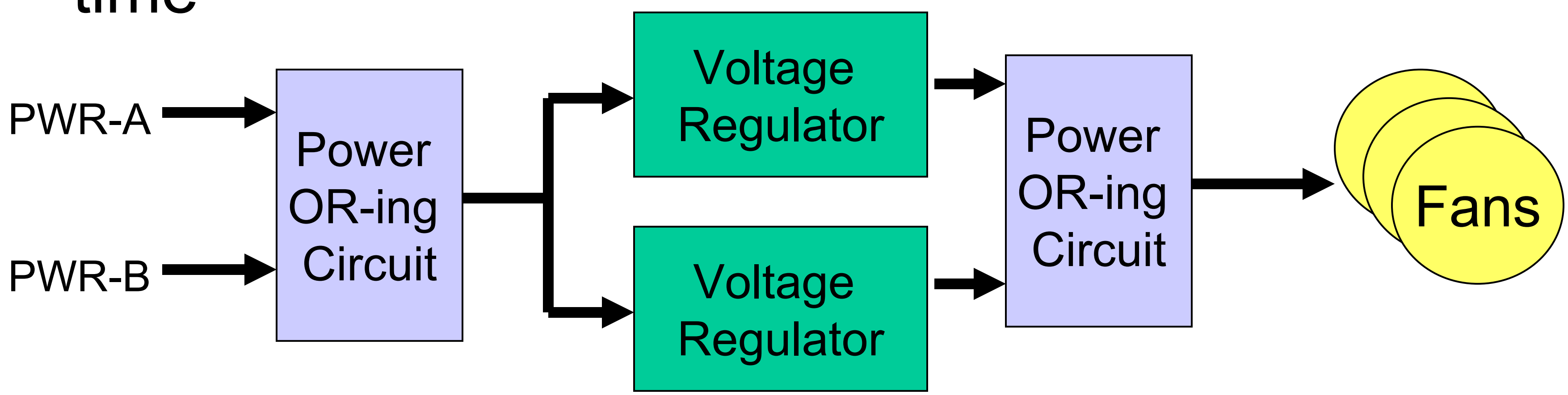
Cons:

- High voltage differentials



Fault Tolerant Design Fan Controller Design

- ❑ Withstands single point failure
- ❑ Significantly increases reliability and up time



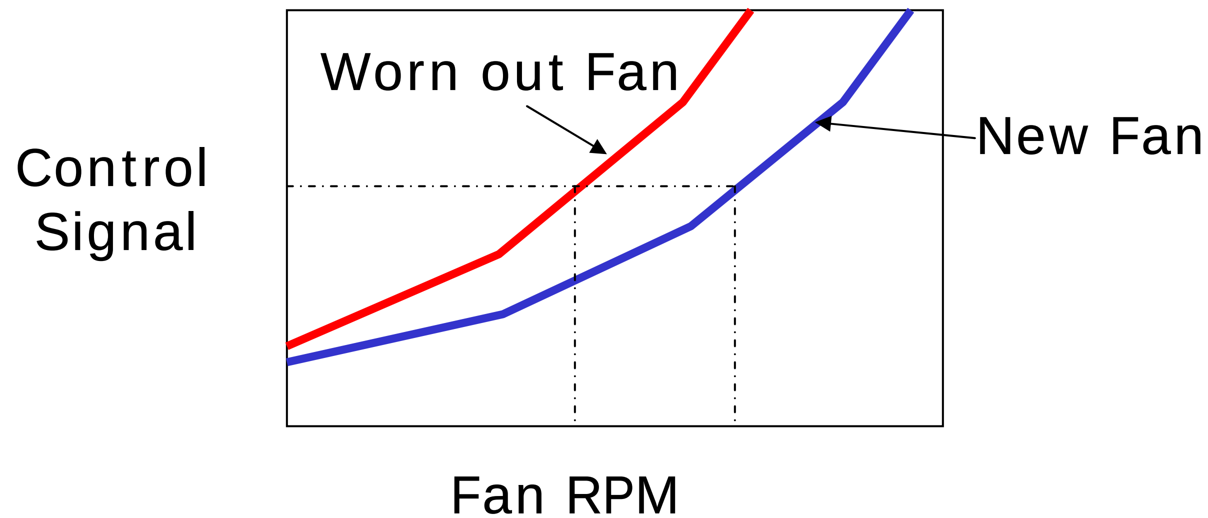
Ideal Power Design

Building Reliability Into Designs

- Maximize reliability of components and blocks
- Implement short term recovery paths for failure
  - Series- Parallel designs
- Monitor faults and enable quick service
  - Fan failure detection
  - Fan failure prediction
  - Filter blockage detection
  - Failure detection in power or control block

Fan failure detection/prediction

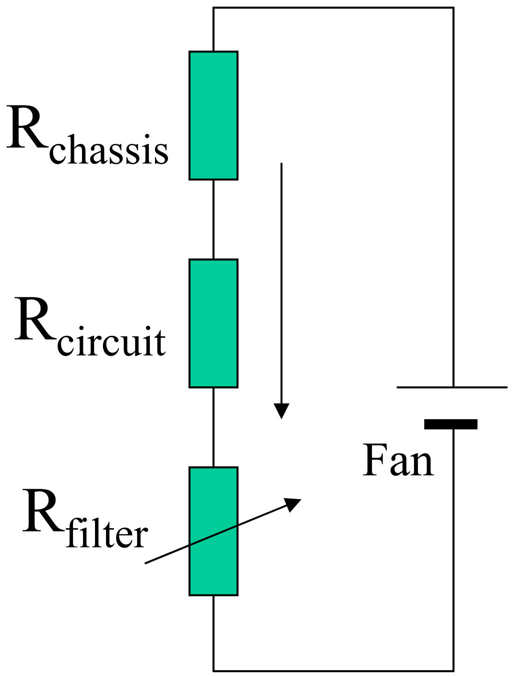
- ❑ Failure detection enables immediate service
- ❑ Failure prediction enables scheduled maintenance



Filter blockage detection

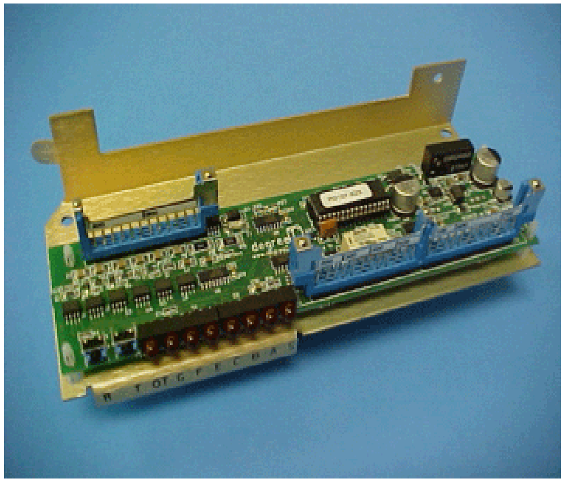
Monitoring Filter resistance through:

- Pressure drop across filter
- Monitoring flow resistance
- Temp rise/fan speed relation
- Cooling capacity monitoring



Thermal Management Controller

- ❑Precise thermal management
- ❑Failure detection and prediction
- ❑Intelligent response to failure conditions for fast recovery
- ❑Designed to provide optimum thermal performance under all conditions
- ❑Adapt as thermal requirements change



Testing

- Device/ Board
- Equipment Chassis
- Data room
- Airflow testing
- Temperature profiling

Device/board Thermal Testing

- On a given board
- At the given airflow
- Operating power conditions
- Ambient temperature
- Heat sinking parts

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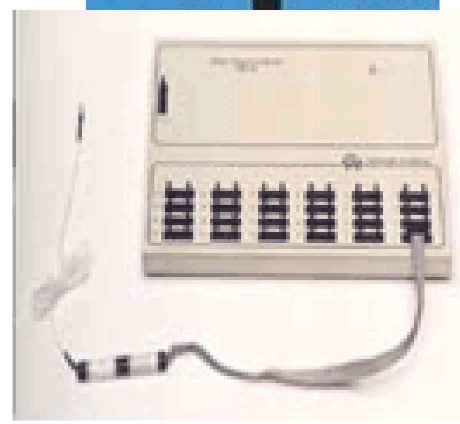
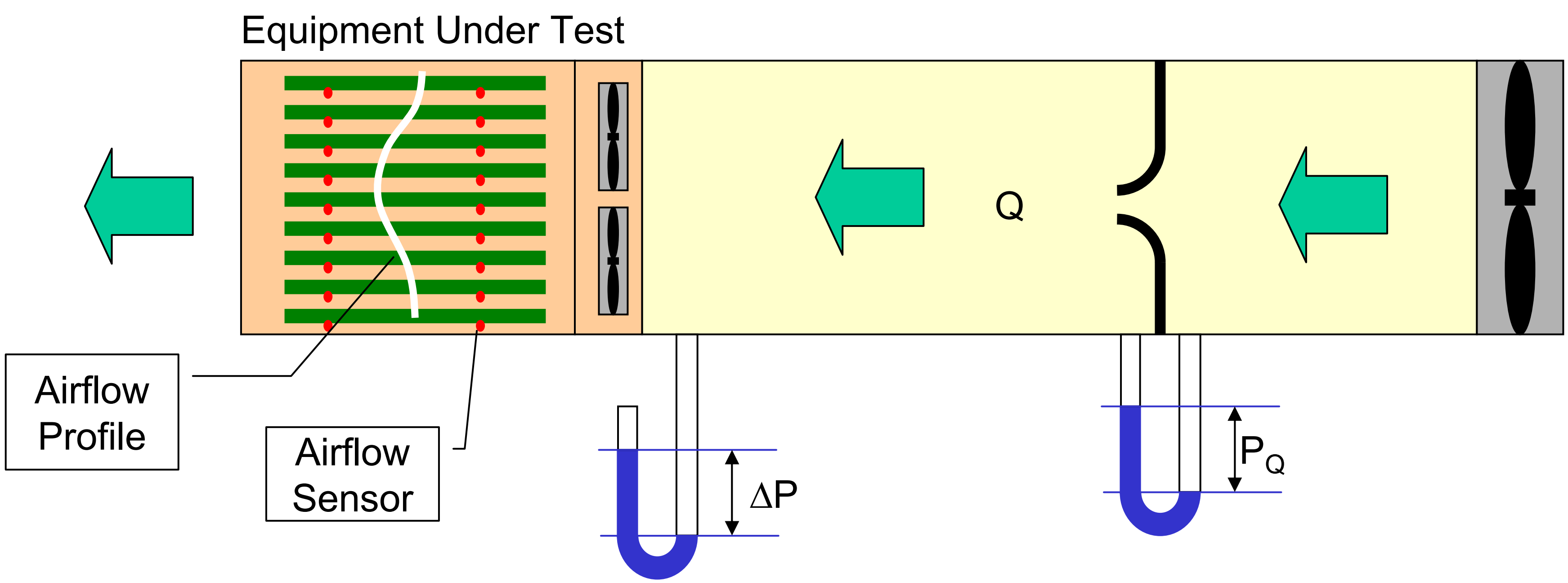
Airflow/Temperature Testing of Equipment

- ❑Monitoring airflow/temp: Multiple points Vs Gross airflow
  - ❖Validating airflow path per design
  - ❖Shadow effect
  - ❖Hot spot development
- ❑Demonstration of ATM24



Flow Test to Study Airflow Distribution



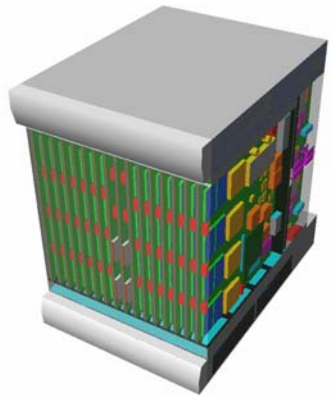
- Get $\Delta P = 0$ by adjusting tunnel flow
- Measure P_Q and calculate Q, gross airflow through EUT
- Measure airflow distribution through circuit packs using a multi-point airflow instrument

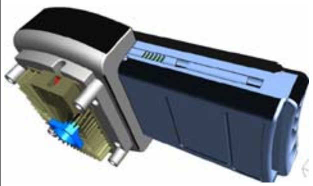
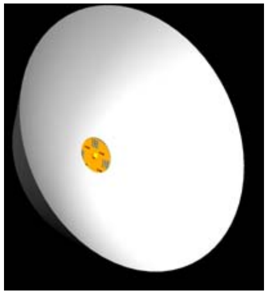
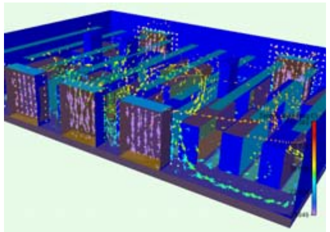
DegreeC: What We Do

- Engineering Cutting Edge Thermal Solutions for Several Target Markets:

Thermal & Flow Technologies

Electronics Products	Process & HVAC	Military	Medical	Telecommunications	Critical Facilities



THANK YOU!